THE CRITICAL INFRASTRUCTURE PORTFOLIO
SELECTION MODEL

A thesis presented to the Faculty of the U.S. Army
Command and General Staff College in partial
fulfillment of the requirements for the
degree

MASTER OF MILITARY ART AND SCIENCE
General Studies

by

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Fort Leavenworth, Kansas
2008

Distribution Statement
Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
13-06-2008	Master's Thesis	AUG 2007 – JUN 2008

4. TITLE AND SUBTITLE
THE CRITICAL INFRASTRUCTURE PORTFOLIO SELECTION MODEL

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Major Travis J. Lindberg

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Command and General Staff College
ATTN: ATZL-SWD-GD
Fort Leavenworth, KS 66027-2301

8. PERFORMING ORG REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS
Critical Infrastructure, Portfolio, Reconstruction, Stability Operations

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. PHONE NUMBER** *(include area code)*
(U)	(U)	(U)	(U)	184	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

MASTER OF MILITARY ART AND SCIENCE

THESIS APPROVAL PAGE

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The opinions and conclusions expressed herein are those of the student author and do not necessarily represent the views of the U.S. Army Command and General Staff College or any other governmental agency. (References to this study should include the foregoing statement.)

ABSTRACT

THE CRITICAL INFRASTRUCTURE PORTFOLIO SELECTION MODEL, by Major Travis J. Lindberg, 184 pages.

This thesis proposes and demonstrates a methodology that enables the user to generate optimal portfolios of projects, based largely on the data envelopment analysis (DEA) approach developed by Israeli professors and industrial engineers, Harel Eilat, Boaz Golany, and Avraham Shtub. The purpose of this methodology, known as the Critical Infrastructure Portfolio Selection Model, is to help policy makers prioritize the allocation of resources while working towards the achievement of short and long term security objectives via the construction, security, and maintenance of critical infrastructure. In order to achieve this end, this thesis modifies the approach developed by Eilat, et al. and applies it to the restoration of essential services and reconstruction of critical infrastructure components within a stability operations environment. The Critical Infrastructure Portfolio Selection Model facilitates this prioritization effort by evaluating a project's ability to transform inputs (budget amounts) into meaningful outputs which are directly linked to strategic measures of effectiveness. The Critical Infrastructure Portfolio Selection Model also offers a holistic and balanced approach to the reconstruction challenge by explicitly incorporating infrastructure project interdependencies and probabilities of project success into the mathematical model by using the concepts of critical node analysis and reliability theory demonstrated by the renowned computer scientist and infrastructure protection expert, Dr. Ted Lewis.

ACKNOWLEDGMENTS

This thesis would not have been possible were it not for the support of several groups of people. First, I would like to thank my thesis committee, Dr. David Anderson, Dr. Sean Kalic, and Mr. Bill Lambert, for their patience and the countless hours that they spent editing drafts, providing unique and useful insights, and advising me on the complex problems associated with reconstruction efforts during stability operations. Second, I would like to thank Colonel Timothy Trainor, PhD, and Lieutenant Colonel Dale Henderson, PhD, from the faculty of the Department of Systems Engineering at the United States Military Academy at West Point. Their foresight to lead an initiative to directly support the reconstruction effort in Iraq, from an academic institution, has provided me with a tremendous example of how to best utilize one’s endowments in order to facilitate the achievement of a worthy strategic end state. Third, I would like to thank my former Department of Systems Engineering cadet capstone team, Second Lieutenants Brandon Corbin, Chris Haag, Chris Miorin, and Erick Taylor, for inspiring me to continue the work that they initiated last year, and for providing me with such rich material to work with. Finally, I would be remiss if I failed to acknowledge the sacrifice made by my wife, Renee, and the rest of my immediate family. Were it not for their unwavering support, I could not have completed this thesis, which has the express purpose of assisting our senior decision-makers make more informed decisions regarding the targeted application of our nation’s scarce resources in support of stability operations. May God bless our most precious resource, our Soldiers, during their efforts to implement these policies.

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ACRONYMS

ASEM	American Society for Engineering Management
CBP	Capabilities-based approach for planning
CERL	Construction Engineering Research Laboratory, ERDC
CI	Critical Infrastructure
CJTF-HOA	Combined Joint Task Force – Horn of Africa
COE	Contemporary Operating Environment
COIN	Counterinsurgency
CSIS	Center for Strategic and International Studies
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
DoDD	Department of Defense Directive
DSE	Department of Systems Engineering
DSS	Decision Support System
ERDC	Engineering Research and Development Center, USACE
FM	Field Manual
GIS	Geospatial Information System
GRD	Gulf Region Division, USACE
GUI	Graphical User Interface
GWOT	Global War on Terror
HN	Host Nation
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IO	Information Operation

IRMO	Iraqi Reconstruction Management Office, Department of State
ISO	International Organization for Standardization
JCC-I/A	Joint Contracting Command – Iraq/ Afghanistan
JEPES	Joint Engineer Planning and Execution System
JFCOM	Joint Forces Command
LOE	Line of Effort
LOS	Level of Service
MCWP	Marine Corps Warfighting Publication
MNF-I	Multi-National Forces – Iraq
MPICE	Measuring Progress in Conflict Environments
NIPP	National Infrastructure Protection Plan
OIF	Operation Iraqi Freedom
O&M	Operations and Maintenance
OR	Operations Research
ORSA	Operations Research/ Systems Analyst
OSD	Office of the Secretary of Defense
PKSOI	Peacekeeping and Stability Operations Institute
PRT	Provincial Reconstruction Team
S/CRS	State Department, Office of the Coordinator for Reconstruction and Stabilization
SDP	System Decision Process
SIGIR	Special Inspector General for Iraq Reconstruction
SME	Subject Matter Expert
SWEAT	Sewer, Water, Electric, and Telecommunication
USACE	United States Army Corps of Engineers

USG	United States Government
USJFCOM	United States Joint Forces Command
USMA	United States Military Academy

ILLUSTRATIONS

CHAPTER 1

INTRODUCTION

> We knew it wasn't a matter of how many projects were completed. It was a matter of: Is the electricity flowing to Baghdad? Is there security on the streets? Is the oil flowing? Those were the things that mattered…Too often, though…it was all about the process – how many hundreds of millions of dollars you had put under contract – and not the product. (2006, 1)
>
> Geoff Witte, *Washington Post.com*

The Need to Transform the Way the Army Plans For and Conducts Reconstruction of Critical Infrastructure in a Stability Operations Environment

There should be little doubt as to the strategic significance that stability operations will play within the contemporary operating environment (COE) for the foreseeable future. With this in mind, in August 2004, Secretary of State Colin Powell created the Office of the Coordinator for Reconstruction and Stabilization (S/CRS). Then, in November 2005, the acting Secretary of Defense, Gordon England, signed Department of Defense Directive (DoDD) 3000.05, which stated that:

> Stability operations are a core U.S. military mission that the Department of Defense shall be prepared to conduct and support. They shall be given priority comparable to combat operations and be explicitly addressed and integrated across all DoD activities including doctrine, organizations, training, education, exercises, materiel, leadership, personnel, facilities, and planning. (DoDD 3000.05, 2005, 2)

To even the most casual observer, there can be little doubt as to the reasons behind the unprecedented levels of interest in stability operations from the highest levels of government in recent years. As of 30 July 2007, total funding for Iraq reconstruction stood at $99.641 billion, with the United States footing $44.538 billion of that amount in appropriated funds (Quarterly Special Inspector General for Iraq Reconstruction (SIGIR)

Report, 30 July 2007, 21). More importantly, as of 25 November 2007, there have been 3873 confirmed fatalities during Operation Iraqi Freedom (OIF) (Iraq Coalition Casualty Count, accessed 25 November 2007 at http://icasualties.org/oif/BY_DOD.aspx). Clearly, the staggering costs associated with engaging in stability operations in Iraq compel the prudent decision-maker to encourage greater inter-agency coordination and seek more efficient and effective ways to allocate our scarce resources as we seek to achieve our national security objectives.

Before proposing a more "optimal" method for allocating these resources, though, it is critical to more fully define and understand the broad general categories (also known as "lines of effort" (LOE)) that we should (or could) choose to allocate our resources within in order to achieve operational objectives within a stability operations environment. Figure 1 is an extract from the Army Counterinsurgency (COIN) Field Manual (FM 3-24) and does an adequate job of depicting an example of what have become the five standard COIN and stability operations LOEs, which are tied together with information operations (IO).

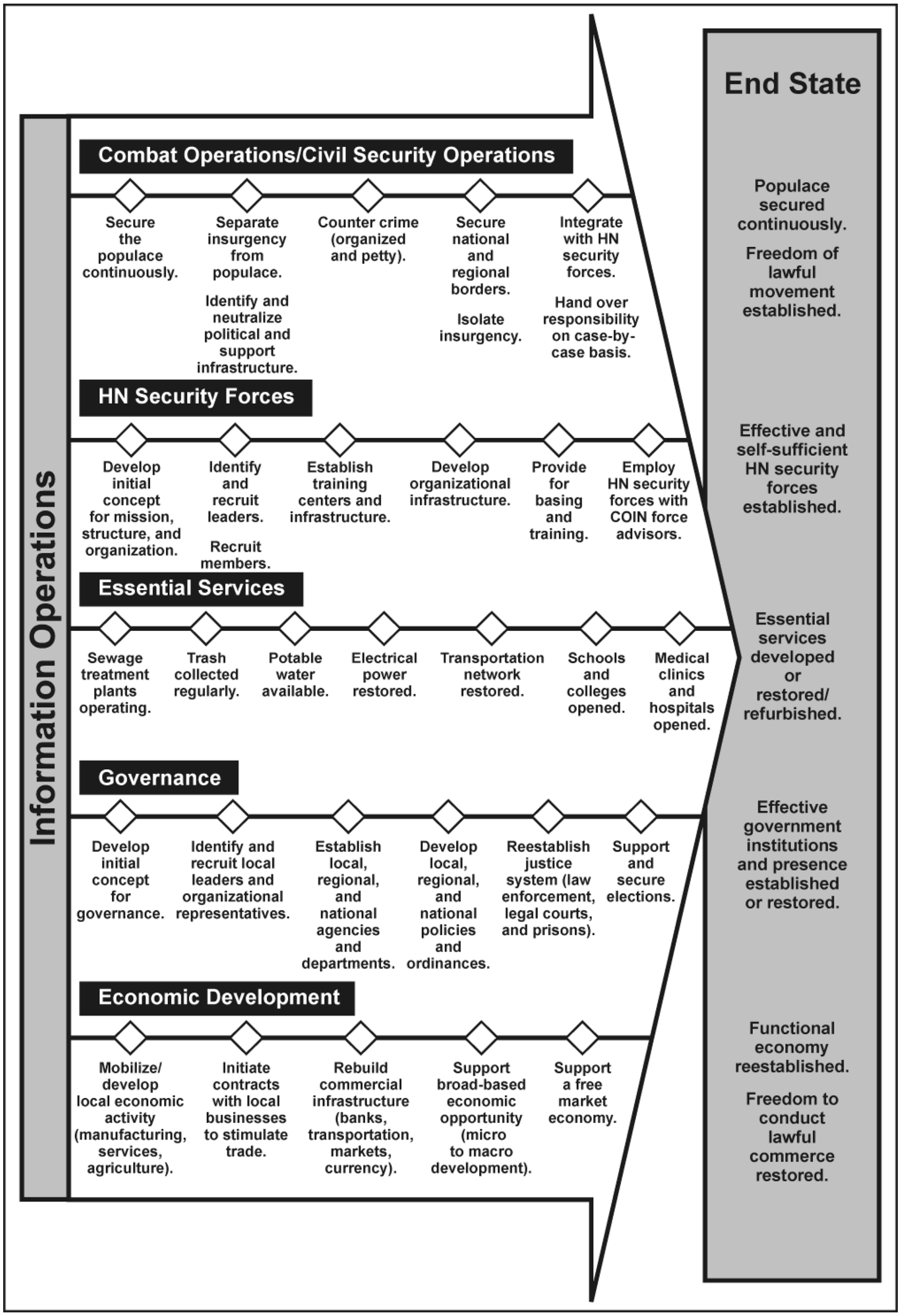


Figure 1. Example of Goals and Objectives Categorized by Lines of Effort (LOE) within a Stability Operations Environment.

Source: HQ Department of the Army, *FM3-24/ MCWP 3-33.5, Counterinsurgency* (HQ Department of the Army, December 2006), 5-5.

It should be noted that while Figure 1 certainly does not accurately depict the synergistic nature of actions and activities within and across the various LOEs in a stability operations environment, Figure 1 does do a good job of implying that a multi-faceted response is required of leaders and policy makers who are confronted with the challenges of a stability operations scenario. More importantly, Figure 1 suggests that failure to develop multi-faceted strategies and policies that promote progress across each of the LOEs will ultimately result in failure to achieve the desired end state in a stability operations environment.

With this in mind, it follows that achieving the desired end state associated with a stability operations mission requires the judicious allocation of scarce resources such as troops, time, money, skilled labor, and specialized equipment across multiple LOEs. Furthermore, the fact that the demand will almost always exceed the supply of these resources will necessarily compel us to determine the temporal order or sequence in which resources must be assigned to tasks across LOEs. By extension, if one considers the temporal order or sequence in which resources must be allocated across these LOEs within a stability operations environment, one must also consider the physical structures and/ or systems upon which each of these LOEs are dependent - critical infrastructure (CI). As a point of clarification, the following definition of critical infrastructure is provided below, based on the United States' National Infrastructure Protection Plan (NIPP):

> Physical or virtual assets, systems, and networks so vital to the United States that the incapacity or destruction of such assets, systems, or networks would have a debilitating impact on security, national economic security, public health or safety, or any combination of those matters (NIPP, Sector Overview, 1).

Clearly, none of the aforementioned LOEs can be pursued, nor can stability operations outcomes be achieved, unless the host nation (HN) infrastructure can be protected, constructed, and maintained. Therefore, before continuing, it is important to understand the relationship between infrastructures, essential services, and several of the aforementioned concepts that will be used throughout the body of this analysis. It is for this reason that Figure 3 attempts to graphically depict the relationships between these critical concepts, while Figure 2 attempts to depict the interdependent relationships that exist among the standard infrastructure sectors as defined by the standard national infrastructure literature.

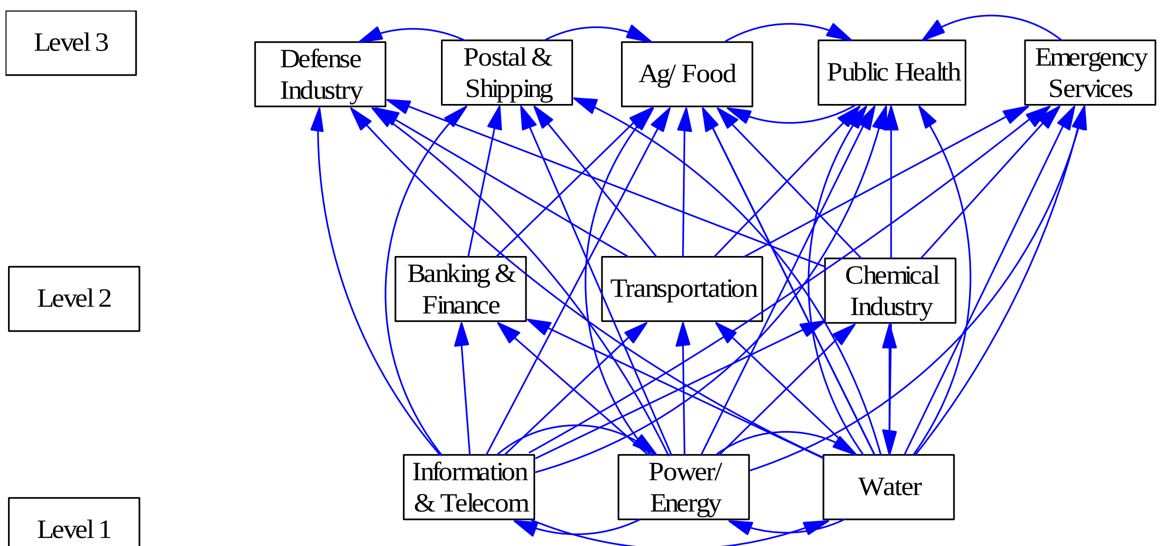


Figure 2. The Author's Depiction of Dr. Ted Lewis' Hierarchy of Critical Infrastructure Sectors as Depicted on the Cover of Dr. Ted Lewis' Textbook, *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation*.

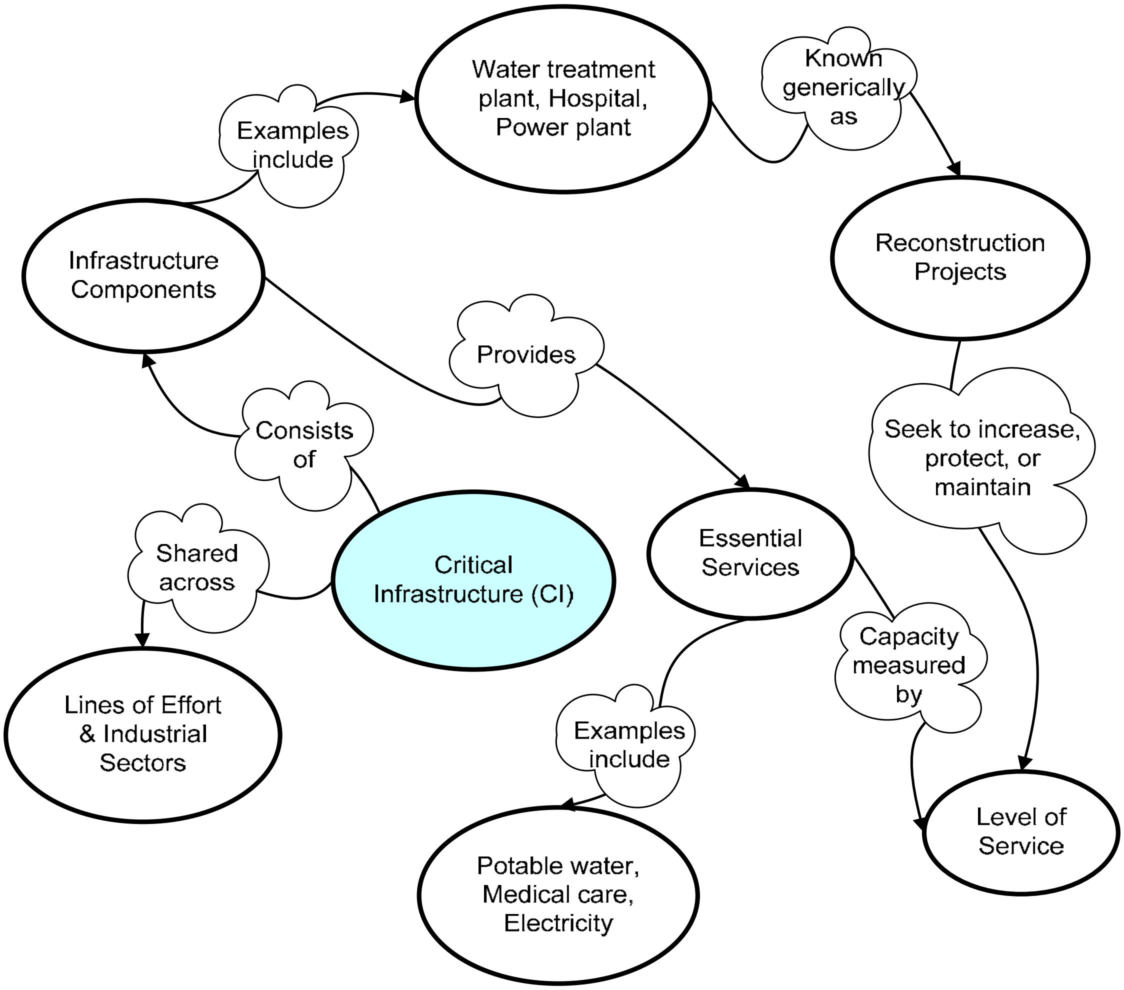


Figure 3. Mapping of Relationships Between Important Terms and Concepts.

Having briefly provided a concept map and definitions, it is important to note that, to date, it appears that throughout the majority of Operation Iraqi Freedom, the reconstruction effort, with respect to CI, has neither been truly “effects-based”, nor focused on providing the greatest value to the Iraqis at the least possible cost to the Iraqis and the international community. Evidence to support the argument that the reconstruction of CI has not been focused enough on eliciting desired effects is provided by two figures which have been extracted from two separate U.S. Army Corps of

Engineers (USACE) Gulf Region Division (GRD) newsletters. The first figure (Figure 4) is a summary of the status of each of the broad sectors of CI found within Iraq (GRD (USACE), 16 June 2006), and based on previous experience, it is a fairly common type of presentation that is used to keep senior-level decision-makers abreast of the reconstruction effort in Iraq. What is important to note is that while this summary uses fairly standard and easy-to-understand metrics to track progress, these metrics do not measure how the coalition reconstruction of CI impact higher-level goals associated with reconstruction, such as reducing the level of violence, or promoting a healthier and more diverse economy. Therefore, having recognized this shortcoming in the way that it portrays its weekly summaries, the GRD decided to shift from measuring progress towards an “End State” within a CI sector (as shown in Figure 4), to attempting to measure “Final Effects” within a CI sector (as shown in Figure 5). Unfortunately, upon further inspection, it appears that the difference in labeling is primarily semantic, since the metrics shown in the “Final Effects” column of Figure 4 are virtually identical to the metrics used to measure progress towards an “End State” – the bottom line being that metrics associated with the reconstruction effort are still not tied to showing progress across other LOEs. Admittedly, the amount of meaningful, “effects-based” metrics that can be depicted in an unclassified, or even FOUO, summary is extremely limited. However, after much correspondence with various analysts and planners from the USACE, Army G3, Joint Staff J5, Joint Forces Command (JFCOM), and Sandia National Laboratory, it is clear that the U.S. Government lacks a coherent and consistent “effects-based” methodology to measuring progress vis-à-vis reconstruction in Iraq.

Sector	Current Status	End State
Electricity	1,431 MW capacity added Increased Power Generation to 1294K Homes Improved Electricity Distribution to approximately 280K Homes	1,562 MW capacity added (2,679 for all USG projects) Increased Power Generation to 1,400K Homes Improved Electricity Distribution to approximately 720K Homes
Oil	2.5 Million Barrels Per Day (MBPD) production capacity 2.1 MBPD produced Natural Gas Production Capacity of 600M standard cubic feet/day	3.0 MBPD crude oil capacity Natural Gas Production Capacity of 800M standard cubic feet/day
Water & Sewer	Added 222,000 cubic meters per day of water treatment capacity (benefits an estimated 1.4 million Iraqis)	Additional 1,245,000 cubic meters per day of water treatment capacity (will benefit approximately 5.8 million Iraqis. All USG projects will benefit 9.33 million Iraqis)

Figure 4. GRD Weekly Construction Update from June 2006.
Source: U.S. Army Corps of Engineers, Gulf Region Division (GRD), "Iraq Reconstruction Report: A Weekly Construction and Sustainment Update," (U.S. Army Corps of Engineers, Gulf Region Division (GRD), 16 June 2006), 8.

Infrastructure Sector	Current Progress	Final Effects
Electricity	1,520 MW capacity added 26 400kv and 132kv Substations 68 33/11kv Substations Hours of Power: Iraq 14, Baghdad 9.8 (Sept. average)	1,983 MW capacity added (2,699 MW for all USG projects) Increased power generation to 1.7 million homes 43 400kv and 132kv Substations 89 33/11kv Substations (126 total for USG) Hours of Power: Iraq 10-12, Baghdad 10-12
Oil	3 Million Barrels Per Day (MBPD) production capacity Over 2.3 MBPD actual production Liquefied Petroleum Gas (LPG) production capacity of 3,000 Tons per Day	3 MBPD oil production capacity LPG production capacity of 3,000 Tons per Day
Water & Sewer	Added 800,000 cubic meters per day of water treatment capacity (benefits an estimated 3.4 million Iraqis)	1,136,000 cubic meters per day of water treatment capacity (will benefit approximately 5.2 million Iraqis. All USG projects will benefit 8.4 million Iraqis)

Figure 5. GRD Weekly Update from 18 October 2007.
Source: U.S. Army Corps of Engineers, Gulf Region Division (GRD), "The GWOT Reconstruction Report: Supporting the Global War on Terror Through Construction and Sustainment, Vol. 1, Issue 7," (U.S. Army Corps of Engineers, Gulf Region Division (GRD), 18 October 2007), 3.

Having addressed the fact that reconstruction efforts to date have generally lacked a genuine “effects-based” approach for measuring the progress of reconstruction in Iraq, it is now time to address the issue associated with failing to pursue reconstruction projects in the most economically efficient manner. For the purpose of this analysis, the term “economical” refers to the “economical performance” of a component of critical infrastructure (CI). Specifically, a component of CI is considered to be economical if it “accomplishes objectives and goals at a cost commensurate with the risk” (Accessed 12 December 2007 at http://www.indiana.edu/~iuaudit/glossary.html). While this definition will be more fully defined in subsequent chapters, an unstated implication associated with this definition is that the objectives or goals across LOEs must be inextricably linked to both the values and the level of expectation of the affected community.

Unfortunately, one need only read a national or international periodical these days and it is clear that the United States has often initiated projects that do not yield value to either the Iraqis or the American people that is commensurate with the costs and risks required to successfully complete the project. In a 2007 *New York Times* article, James Glanz cites numerous instances in which CI reconstruction projects have been built in Iraq, only to fall into disrepair or disuse almost immediately after the following contractor has departed the project site (Glanz, 2007, 1). What’s more, these allegations are further corroborated by anecdotal evidence presented by numerous military officers and academics that have spent, in many cases, considerable amounts of time within the theater of operations since the spring of 2003.

Clearly, in spite of the best intentions of the majority of the individuals working within the Iraqi Reconstruction Management Office (IRMO), the GRD, and the host of

other governmental and non-governmental organizations responsible for identifying reconstruction priorities and managing reconstruction efforts within Iraq, a new methodology is required. This new methodology must do a better job of identifying possible, or at least likely, effects that are felt across lines of effort (LOE), as well as identifying reconstruction projects that accomplish objectives and goals across LOEs at a cost commensurate with the risk. Yet decision-makers seeking to utilize such a methodology in order to justify strategic and operational-level policies would be well served by ensuring that such a methodology does not impose yet an additional unrealistic data/ intelligence collection requirement upon the tactical level organizations doing the data and intelligence gathering. The ideal situation would be one in which the proposed methodology could harness data that is relatively easy to obtain, and of use to multiple organizations.

Benefits Associated with the Critical Infrastructure Portfolio Selection Model

The Critical Infrastructure Portfolio Selection Model is a proposed methodology for overcoming previously identified shortcomings associated with reconstruction efforts in stability operations environments such as in Iraq and Afghanistan. While the details of this methodology will be laid out more comprehensively in the remainder of this paper, this section will outline the salient features of the methodology. In the most general terms, the Critical Infrastructure Portfolio Selection Model is an operations-research (OR) based portfolio selection method which operates under the assumption that there is a combination of critical infrastructure (CI) projects that can optimize benefits to an affected population across lines of effort (LOE) at costs that are commensurate with risk. For the sake of clarity, the use of the term “portfolio” in this thesis will merely be to refer

to a collection of distinct reconstruction projects that are simply components of critical infrastructure. However, it should be noted that a project which consisted of adding capacity to a water treatment plant, could be distinct from: 1) A possible project to increase security measures around the water treatment plant; or 2) A possible project to invest in the operations and maintenance (O&M) of the water treatment plant. Figure 6 attempts to graphically portray this methodology as an input-output model.

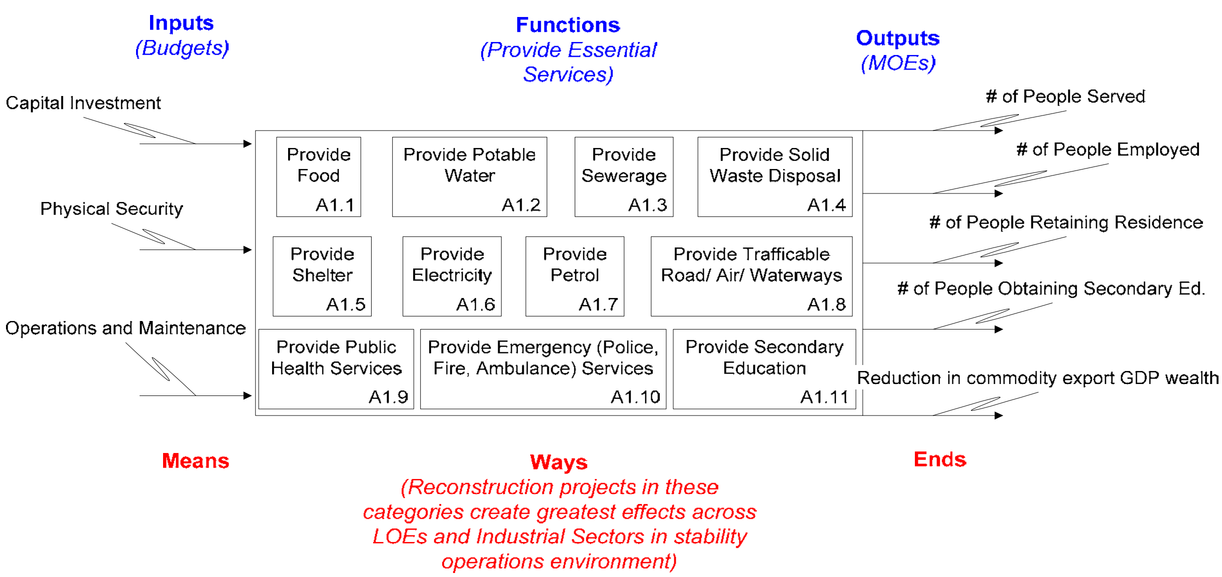


Figure 6. The Critical Infrastructure Portfolio Selection Model Transforms Inputs into Useful Outputs.

In addition to this new methodology potentially doing a better job of identifying possible effects that are felt across lines of effort (LOE), as well as identifying reconstruction projects that accomplish objectives and goals across LOEs at a cost commensurate with the risk, it offers several other benefits as well. First, the intent is that this model would be utilized as a decision support system (DSS) to support commanders in the field. One of the major impediments to fielding a DSS is a lack of

usable data. However, the advantage of this model is that it seeks to use existing USACE and other governmental agency data sources with respect to critical infrastructure. It is also ideally suited for inclusion in a future version of the Joint Engineer Planning and Execution System (JEPES), an automated planning tool that is managed by JFCOM, for the same reasons. Additional similarities to models possessing "best practices" characteristics, along with their inherent benefits, will be addressed in the following chapter.

Assumptions Associated with the Critical Infrastructure Portfolio Selection Model

The first major assumption associated with the Critical Infrastructure Portfolio Selection Model is that the perceived legitimacy of a host nation government is directly correlated to that government's ability to provide essential services to its people. More importantly, in order for a society to function properly, the duly recognized civil authority must effectively manage its infrastructure in order to provide its citizens with essential goods and services. Thus, the conditions of poor governance and degraded infrastructure are strongly positively correlated and will inevitably lead to, or are the byproducts of, a failed, or failing, state in which essential services are either lacking or non-existent.

The second major assumption associated with the Critical Infrastructure Portfolio Selection Model is the notion that the stability of people and institutions within the operating environment are influenced by several factors, but one of the most important, and the one that this thesis will primarily consider, is the length of time that it takes a government to re-establish essential services. The amount of time available before a society descends into chaos is called the "Golden Hour." Thus, a related assumption is

that the relationship between time with inadequate essential services and magnitude of social unrest is non-linear. Hence, stability operations environments will have a tendency to grow “exponentially” worse as more time elapses before essential services are restored.

The third major assumption associated with the Critical Infrastructure Portfolio Selection Model is that it is impossible to directly measure any of these conditions and effects in the COE, hence proxy measures must be developed which are closely aligned with actual effects that policy-makers are trying to achieve. While some may eschew this notion of “attempting to quantify the unquantifiable,” leaders who have the burden of assigning scarce resources to requirements (projects/ tasks/ missions) do not have this luxury and must have tools at their disposal that enable them to make the best decisions possible which will permit the attainment of national security objectives. Alternatives such as using crude rules of thumb, or simply throwing money at the problem, while necessary in some cases, should be avoided if a more effective methodology is available.

The final major assumption associated with the Critical Infrastructure Portfolio Selection Model is that “Pareto’s rule” will hold true in most cases. That is to say, in very simple terms, that eighty percent of the effects (or value) will be achieved with twenty percent of the population under consideration. While certainly a bastardized version of Vilfredo Pareto’s actual observation, this assumption is commonly understood and generally accepted across multiple domains, especially business management and military operations. Thus, it is a rule of thumb that will be utilized consistently when trying to pare down alternatives in the analysis chapter of this thesis.

CHAPTER 2

LITERATURE REVIEW

Given the diverse nature of the topics that must be addressed in order to explain the nature and purpose of the Critical Infrastructure Portfolio Selection Model, it is necessary to categorize the literature into four major groups. The first body of literature that will be reviewed relates to the quantitative methods that have been used to assist in the multi-criteria decision making process. This body of literature is crucial since it provides a justification for the mathematical structure of the Critical Infrastructure Portfolio Selection Model. The second body of literature relates to critical infrastructure (CI) sectors and components, especially as they relate to the analysis of interdependencies among CI sectors and components across lines of effort (LOE). The third body of work is the effects- and capabilities-based literature, as well as “systems thinking” concepts, as it applies to stability operations and reconstruction environments. The final body of work is the conflict initiation and termination literature that has been driven largely by the World Bank. This final category of literature is vital, since it provides the context for the primary research question under investigation, and also provides a partial, quantitatively-supported justification for the selection of measures of effectiveness (MOEs) employed by the Critical Infrastructure Portfolio Selection Model.

Portfolio Selection Using Quantitative Methods

The first body of literature addresses the analytical (quantitative) techniques that are used as the theoretical and mathematical framework for the Critical Infrastructure Portfolio Selection Model and can be further subdivided into three sub-categories: Data

Envelopment Analysis (DEA), Input-Output Modeling, and Portfolio generation using the DEA methodology. Subhash Ray's 2004 text, *Data Envelopment Analysis [DEA]: Theory and Techniques for Economics and Operations Research* provides an excellent overview of the first quantitative sub-category. As stated previously, the purpose of DEA is to enable a decision-maker to evaluate how effectively the decision making units (DMUs) convert resources (inputs) to benefits (outputs). If a DMU converts resources to benefits with 100% "DEA efficiency," the DMU receives a score equal to one (1.0). Conversely, if a DMU converts inputs to outputs poorly, then that project receives a score less than one, but greater than or equal to zero (0.0). In terms of what a DMU might represent in reality, consider a restaurant owner who owns a set of restaurant franchises. That owner is justifiably interested in knowing which restaurants turn a profit or provide quality service, both necessary benefits (outputs), based on the quantity of resources (inputs) he has allocated to them in terms of labor, new equipment, etc. In the restaurant owner's problem scenario, the restaurant would be classified as the DMU, since the owner, armed with this information, could then (theoretically) best decide how to allocate the remainder of his current and future resources towards each of his restaurants.

In the context of the Critical Infrastructure Portfolio Selection Model that is described within this thesis, the DMUs are CI reconstruction projects. Just like the aforementioned restaurant franchise owner, a leader in a stability operations environment has a fundamental decision, or set of decisions, to make: How to best allocate resources (inputs) across a set of critical infrastructure projects so that one might obtain the greatest possible effects (outputs)? Data envelopment analysis, by virtue of its ability to take

large data sets of quantitative and qualitative factors associated with DMUs (reconstruction projects), is a popular method for conducting this type of analysis.

However, despite the widespread use of DEA as an analytical technique, Ray does list two notable disadvantages. The first disadvantage that Ray acknowledges is that since DEA models are non-parametric in nature, they do not yield a single mathematical function from which costs and profits can easily be derived (Ray, 2004, 2). The second disadvantage, which is related to the first, is the fact that since DEA is a non-parametric statistical technique, the output from a DEA model does not produce a standard error, which prevents it from being used to directly test a hypothesis (Ray, 2004, 2). While these disadvantages may mean that the Critical Infrastructure Portfolio Selection Model is unable to produce a single, closed-form, regression-type equation that is capable of being tested using standard hypothesis-testing techniques, a discussion of the following two sub-categories of quantitative methods under consideration will demonstrate the utility of the DEA approach.

With this being said, the next sub-category of literature that addresses the application of quantitative methods in reconstruction (stability) operations is related to Input-Output modeling. Like DEA, Input-Output models are based upon a linear programming (mathematical) model framework. That is to say, that both DEA and input-output models require the use of a special computer program, such as MS Excel's built-in solver program, to solve the system of mathematical equations that define the nature of their constituent relationships. However, while DEA attempts to gauge relative efficiencies of DMUs, input-output models attempt to quantitatively measure the degree of interdependencies among system components. With this in mind, the article titled

Input-Output Modeling for Assessing Cascading Effects and written by Dr. Mark Gallagher, Captain (USAF) Anthony Snodgrass, and Major (USAF) Gregory Ehlers ties together two concepts that are fundamental to enabling a thorough understanding of the Critical Infrastructure Portfolio Selection Model: effects-based operations (EBO), to include military center-of-gravity (COG), or strategic attack, analysis; and system interdependency, or input-output, analysis. While the average military reader is probably already familiar with the concept of center-of-gravity analysis, the average reader may not be as familiar with input-output analysis. As stated previously, like DEA, input-output analysis is another linear programming (LP) technique. However, input-output analysis was developed by Wassily Leontief (earning him the 1976 Nobel Prize in economics) in order "to make economic assessments based on the interdependencies of various production sectors within a region" (Gallagher, et al., 2005, 5). After a basic overview of the history and the mathematical structure of the input-output model, Gallaher, et al. present various case studies which demonstrate the utility of input-output analysis in a variety of scenarios. Fortuitously, one of their case studies included an application oriented towards "nation-building." Of equal use is the authors' discussion of the assumptions associated with Leontief's input-output model (Gallagher, 2005, 8 – 9). Specifically, they state that one of Leontief's primary assumptions was that, "by aggregating at the proper level,… the output of each [industrial] sector may be measured on a single scale, such as dollars or units of production appropriate for that industry" (Gallagher, 2005, 7). They also emphasize that just because the structure of the underlying economic model is linear in nature, does not mean that the impacts experienced throughout the economic system will be linear in nature (Gallagher, 2005,

11). With regards to the proposed Critical Infrastructure Portfolio Selection Model, the significant implication of the prior statement is that as long as the parameters of the model have been aggregated at the appropriate level of governance, a leader may use the model to determine what impact even the smallest investment (input) in an infrastructure project might have across several measures of effectiveness (MOEs) that, in turn, span multiple LOEs.

The final sub-category considered within the analytical (quantitative) technique category of literature serves as the primary mathematical foundation for the Critical Infrastructure Portfolio Selection Model. This sub-category is dedicated to the investigation of a quantitative method that has been developed to exploit the DEA and input-output methods expressed earlier. This method, described in a journal article written in 2005 by Harel Eilat, Boaz Golany, and Avraham Shtub titled, *Constructing and Evaluating Balanced Portfolios of R&D projects with Interactions: A DEA Based Methodology,* results in a technique for selecting an "efficient" group projects from a total set of possible projects, based on various input and output parameters for each of the projects. While the authors apply this technique within a research and development (R&D) portfolio selection scenario, the method can easily be modified to meet just about any situation in which similar conditions exist, as is the case with the Critical Infrastructure Portfolio Selection Model. While the authors' methodology relies heavily on much of the same quantitative background that has already been introduced, their primary contribution to the portfolio selection literature is their introduction of an "accumulation function" as a means of aggregating the input and output interactions that occur between individual projects within various portfolios (Eilat, et al., 2005, 1026).

The end result is that the authors' model enables the decision-maker to prioritize portfolios of projects, which explicitly account for interdependencies among the individual projects within a portfolio, as opposed to simply attempting to prioritize individual projects. However, it should be noted that while the fundamental structure of the Critical Infrastructure Portfolio Selection Model will closely duplicate the structure of the portfolio selection methodology proposed by Eilat, et al., there will be some differences between the two, most notably in terms of the way that project risk is assessed.

Critical Infrastructure Components and Interdependencies Between Components

The second body of pertinent literature attempts to codify and analyze the various functions and engineering aspects of, as well as relationships between, critical infrastructure components. Of greatest significance is the literature that attempts to define the types of relationships (interdependencies) that exist between infrastructure sectors and infrastructure components, which exist within sectors. This section also includes an examination of sector-specific documents that have been, and are still being, used by infrastructure sector (ministry) officials in Iraq. This section concludes with a review of literature related to existing information management systems that should be considered prior to attempting to implement any automated decision-support tool that utilizes the algorithm based on the Critical Infrastructure Portfolio Selection Model.

As stated previously, one of the most insightful articles reviewed within this category was written by prominent scientists and policy advisors Steven Rinaldi, James Peerenboom, and Terrence Kelly titled *Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies*. Written before the 9/11 terrorist attacks, the

article is not oriented on preventing critical infrastructure failures due to a terrorist attack, rather, the article was focused on preventing the types of cascading infrastructure failures that occurred during the aftermath of the electric power disruptions in California earlier that year. As a point of clarification, a cascading failure is a situation in which the failure of a seemingly insignificant critical infrastructure component (e.g. power line) propagates failures across seemingly unrelated infrastructure sectors – the Northeast Blackout of 2003 is the most widely cited contemporary example. With that in mind, Rinaldi, et al. helps establish and define the types of interdependencies that exist between and within "complex adaptive systems." The authors then provide a taxonomy of the types of interdependencies and possible failure modes that might exist within infrastructure networks (Rinaldi, 2001, 11 – 24). Given the authors' advisory roles on senior policy panels, coupled with their credibility as scientists affiliated with national laboratories (Argonne and Sandia) and academia, it should come as no surprise that their article has influenced many of the tools and decision support systems that exist within the infrastructure protection and infrastructure reconstruction domains, both domestically and internationally. Evidence supporting this claim is born out in Figure 7, which, even though not taken from the Rinaldi, et al. article, concisely summarizes the major points of the article.

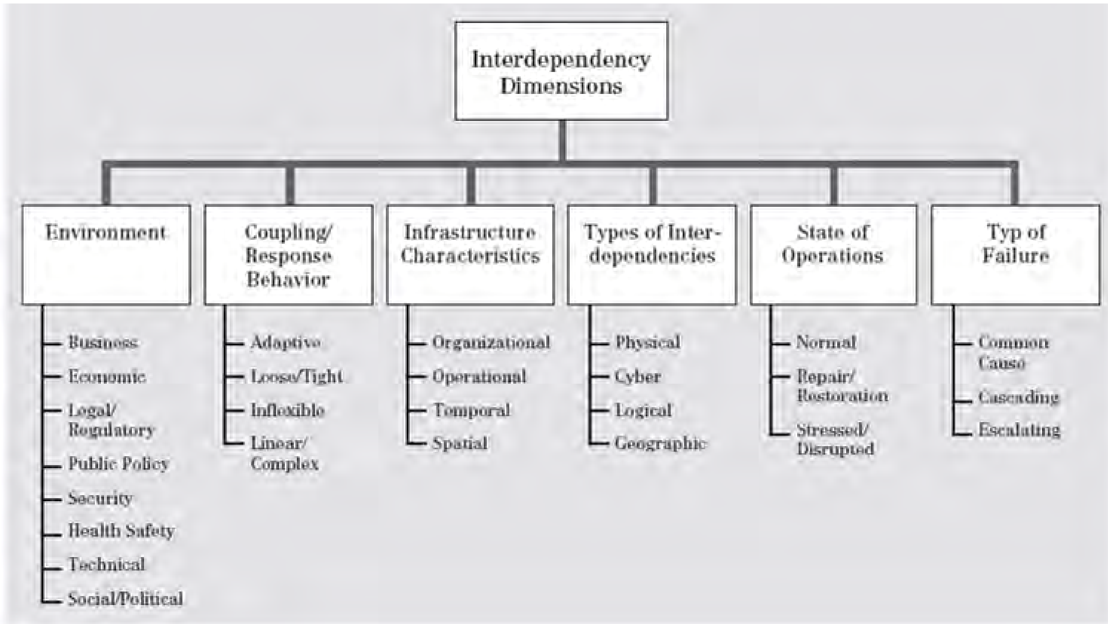


Figure 7. Critical Infrastructure (CI) Interdependency Dimensions.
Source: Wenger, Andreas, Jan Metzger, and Myriam Dunn, editors, *International CIIP Handbook: An Inventory of Protection Policies in Eight Countries*, *Volume 1* (Zurich, Switzerland: Center for Security Studies, ETH Zurich, 2002), 165. This figure is derived from the article written by Rinaldi, et al.

Utilizing much of the same mathematical foundation as the aforementioned reference, the 2006 text *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation*, by Dr. Ted Lewis, an expert in computer science and national security affairs, is arguably the nation's preeminent reference on developing sound policies for the protection of the nation's critical infrastructure while using the optimal allocation of resources to do so. The most useful pieces of information to come from Lewis include a mathematically precise definition of (project) risk (Lewis, 2006, 145 – 187), as well as a thorough definition of the concept of "critical node analysis" (Lewis, 2006, 16 – 22). In the most basic terms, Lewis describes the "critical node" of an infrastructure network as the "hub," from which the spokes of the infrastructure emanate

(e.g. transportation system, power generation and distribution system). Lewis demonstrates mathematically that the most sound infrastructure protection policies are those that minimize risk and allocate resources towards protecting the "critical nodes." In an attempt to relate the notion of interdependence and dependence amongst infrastructure sectors, discussed previously, and Lewis' notion of a "critical node," the reader is directed towards the image taken from the cover of Lewis' text (see Figure 8).

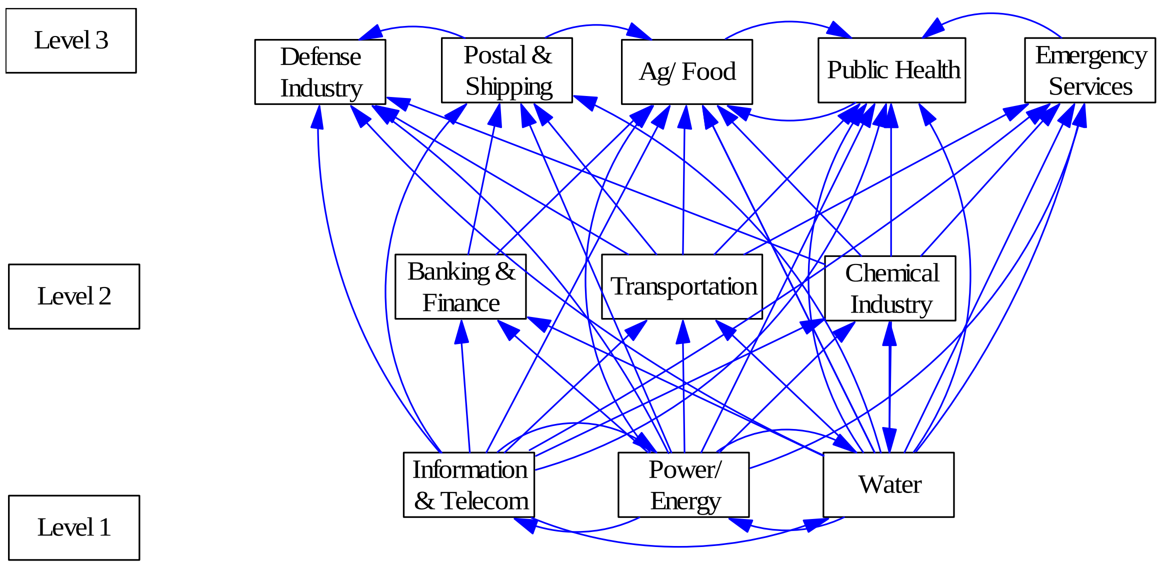


Figure 8. The Author's Depiction of Dr. Ted Lewis' Hierarchy of Critical Infrastructure Sectors as Depicted on the Cover of Dr. Lewis' Textbook.

One can clearly observe in Figure 8 that the Level 2 and Level 3 (top) infrastructure sectors found within a modern society are dependent upon those infrastructure sectors which constitute the "Level 1" (bottom) sectors, Information and Telecom, Power/ Energy, and Water/ Sewage. While more time will be spent analyzing the implications of the relationships depicted in Figure 8 within Chapter 4 of this thesis, one can see that each of the sectors (and their constituent critical infrastructure components) residing in Level 1 clearly exhibit the "critical node" characteristics mentioned previously.

Therefore, Lewis argues that if one wants to improve the resilience of the system, which yields the greatest possible benefits to the people and economies dependent upon these infrastructure sectors, one must allocate the majority of one's budget dollars to reducing risk in the "critical nodes," which may occur in both sectors and components within sectors. While a more thorough explanation of risk is provided in the following chapter of this thesis, it is important to note that two national policy documents addressing the protection of domestic infrastructure, *The National Strategy for the Physical Protection of Critical Infrastructure and Key Assets* (2003) and the *National Infrastructure Protection Plan (NIPP)* (2006) are predicated on the logic espoused by Lewis and several of the aforementioned authors. Furthermore, instead of applying Lewis' mathematical models in an effort to simply protect domestic (U.S.) critical infrastructure, the *Critical Infrastructure Portfolio Selection Model* uses Lewis' approach to prioritize the (re)construction, protection, and maintenance of CI components in a stability operations (foreign) environment.

Unfortunately, as relevant as Dr. Lewis' text is, it became readily apparent after numerous interviews with a British provincial reconstruction team (PRT) operating out of Basra, Iraq that one cannot simply apply analytical techniques, which are intended to optimize the allocation of resources to protect critical infrastructure within the United States, to the reconstruction efforts within most stability operations environments. A teleconference between USMA faculty members and British PRT members on 11 April 2007 provided valuable insight as to the actual needs of both foreign and host nation planners and managers in Basra, Iraq. Specifically, the PRT outlined their need for assistance in operations and management, and the optimization of processes to support

planning as it applied to three major infrastructure sectors: power, water, and sewerage (Henderson, 2007, 1 – 2). Furthermore, two of the USMA team members, Colonel Tim Trainor and Lieutenant Colonel Dale Henderson, deployed to Basra, Iraq during the summer of 2007 in an attempt to provide expert advice and mentorship within the aforementioned assistance areas within the Basra Water Ministry. Lessons learned from this deployment, and about the relationship between infrastructure reconstruction efforts and the role of government, are encapsulated within a presentation given at the 2007 annual conference of the American Society for Engineering Management (ASEM) (Henderson, et al, 2007).

To facilitate their research efforts in support of the Basra water ministry, the USMA team had access to two primary documents that helped offer insight into the infrastructure needs of the Iraqi people. The first document was *The Feasibility Study on Improvement of the Water Supply System in Al-Basra City and its Surroundings in the Republic of Iraq*, by Tokyo Engineering Consultants Co, LTD., and Nippon KOEI CO., LTD., October 2006. The feasibility study provided an in-depth analysis of the major, and minor, water infrastructure reconstruction projects that the Basra government hoped to undertake over the next ten to fifteen years. It provided a comprehensive data set, to include itemized (estimated) costs associated with each of the projects. The second document was the *Water Sector Investment Planning, Al Basra Sewerage Directorate*, by Mott McDonald, August 2004. It offered similar insights into the sewage needs of the Basra community. What was clear during the review of each of these documents was that neither analyses included a meaningful examination of the nature of relationships (either interdependencies or dependencies) between the different projects within their respective

sectors (i.e. water and sewer), much less an examination of the nature of the relationships with other infrastructure sectors or lines of effort, such as economic development. Nor were project risks examined in an appropriate level of detail given the unstable and unpredictable environment in which these infrastructure components would be operating. Therefore, it would probably not be too much of an extrapolation to assume that these same types of analytical oversights are common in other, much less thorough, reconstruction analyses within other stability operation environments.

The final sub-category within this second body of literature includes works related to the various information management systems that have been developed to manage the infrastructure intelligence, geospatial, and information systems that are ubiquitous within the contemporary operating environment (COE). One of the tools that falls into the aforementioned categories is the Geospatial Assessment Tool for Engineer Reachback (GATER). The GATER is a system of integrated hardware and software that was developed by the Engineer Infrastructure and Intelligence Reachback Center (EI2RC), an organization within the USACE Mobile, Alabama District Headquarters. The primary components of the GATER are depicted in Figure 9. For the sake of simplicity, it is sufficient to say that the system initiates when a soldier or civilian trained on the use of the system seeks to obtain essential information about the state of CI within an affected area using the “It Knows Everything” (IKE) handheld device. The data captured by the IKE is then transferred to a desktop computer, and further transmitted to the central infrastructure database which is managed by the EI2RC. Once the infrastructure intelligence is transferred to the database, it can then be shared with

numerous governmental agencies via the Non-Classified Internet Protocol Router (NIPR) or Secret Internet Protocol Router (SIPR) networks.

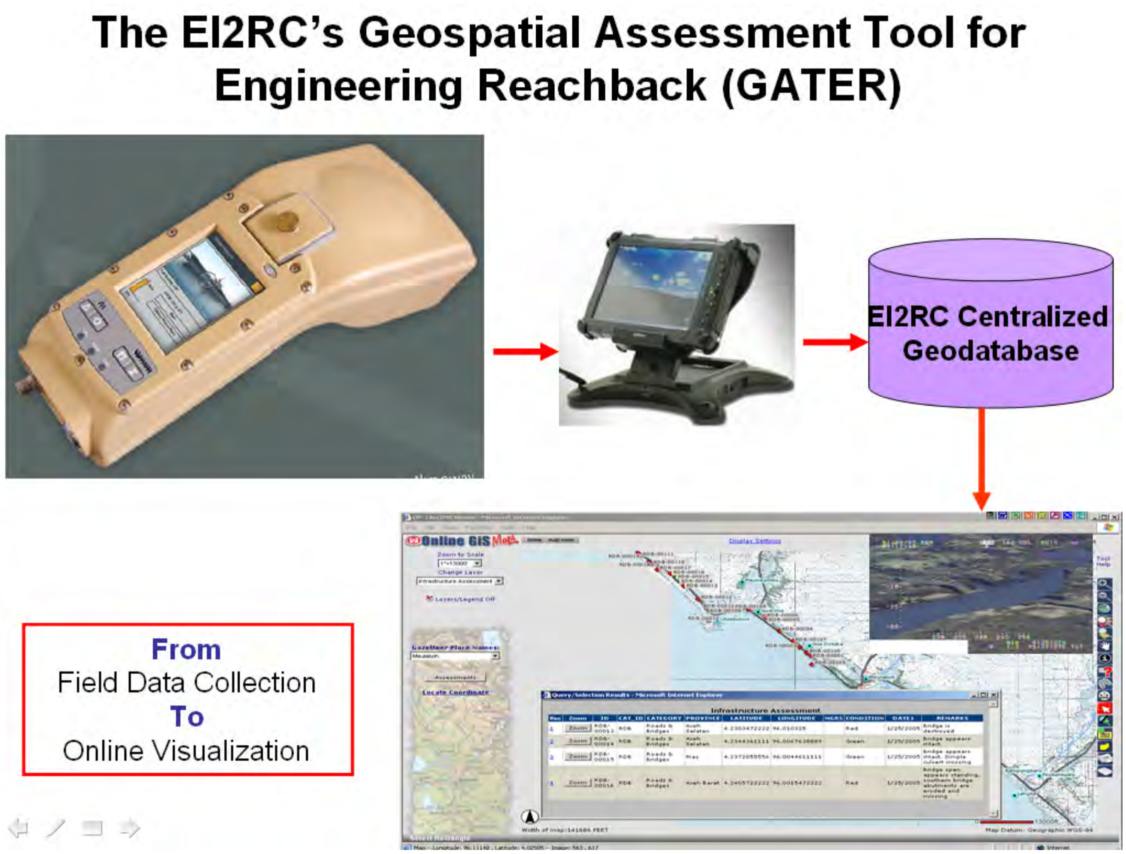
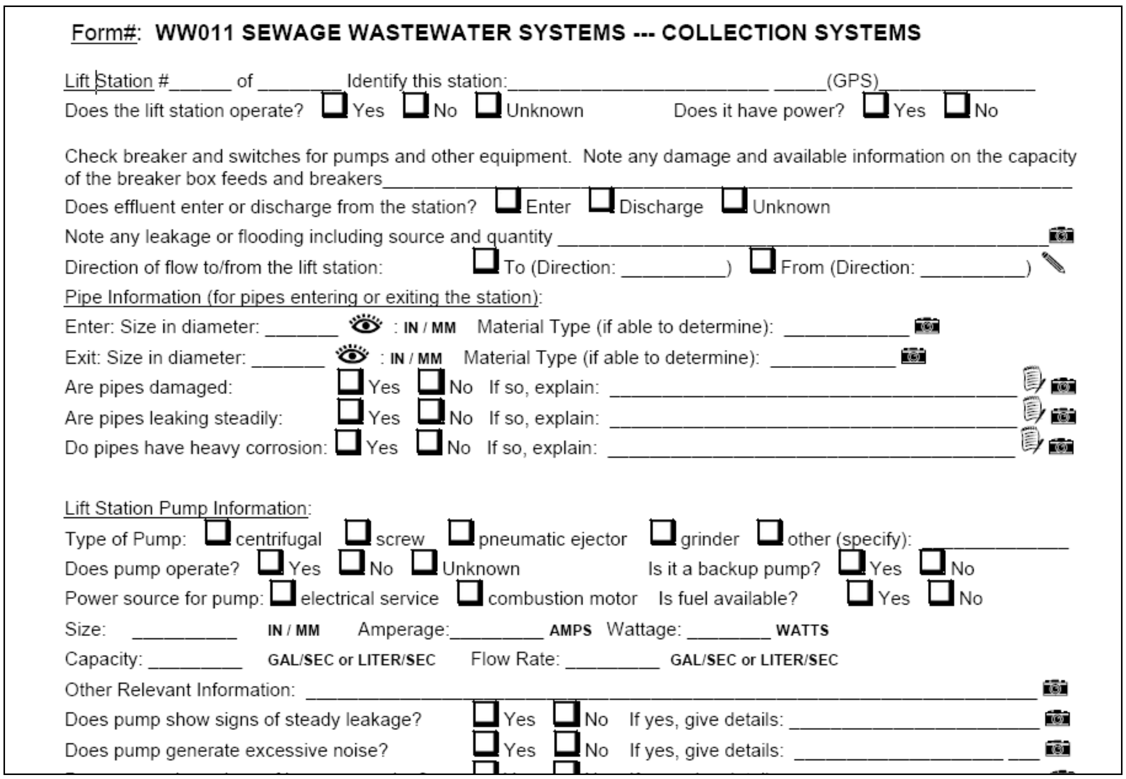


Figure 9. Basic Architecture of the GATER Data Exchange Utilizing the IKE Handheld Device (upper left) and the EI2RC Web Portal (lower right).
Source: Hardegree, Unpublished presentation on the *Engineering Infrastructure and Intelligence Reachback Center (EI2RC)* (Mobile, Alabama District, U.S. Army Corps of Engineers (USACE), 8 August 2006), Slide 4.

It should also be noted that the GATER system utilizes the DoD real property standard in order to classify infrastructure. While these DoD real property categories are not aligned with the national infrastructure protection literature sectors, this lack of alignment should be transparent to the user and serve as a useful standard within the Critical Infrastructure Portfolio Selection Model's data management layer.

A non-automated, yet more detailed, analog (paper) version of the GATER system has also been developed by USACE. The Sewer, Water, Electric, and Telecommunications *(SWEAT*) *Books*, *Volumes 1 – 3* were developed in response to military units' requests to assist them in performing infrastructure inspections in Iraq. The purpose of the SWEAT books, like the GATER, is to help facilitate the gathering of pertinent critical infrastructure intelligence so that leaders can better allocate scarce resources to help restore basic services.



Form#: **WW011 SEWAGE WASTEWATER SYSTEMS --- COLLECTION SYSTEMS**

Lift Station #______ of ________ Identify this station:________________________ _____(GPS)______________
Does the lift station operate? ☐ Yes ☐ No ☐ Unknown Does it have power? ☐ Yes ☐ No

Check breaker and switches for pumps and other equipment. Note any damage and available information on the capacity of the breaker box feeds and breakers____
Does effluent enter or discharge from the station? ☐ Enter ☐ Discharge ☐ Unknown
Note any leakage or flooding including source and quantity ____
Direction of flow to/from the lift station: ☐ To (Direction: _________) ☐ From (Direction: _________)
Pipe Information (for pipes entering or exiting the station):
Enter: Size in diameter: _______ : IN / MM Material Type (if able to determine): ___________
Exit: Size in diameter: _______ : IN / MM Material Type (if able to determine): ___________
Are pipes damaged: ☐ Yes ☐ No If so, explain: ______________________________________
Are pipes leaking steadily: ☐ Yes ☐ No If so, explain: ______________________________________
Do pipes have heavy corrosion: ☐ Yes ☐ No If so, explain: ______________________________________

Lift Station Pump Information:
Type of Pump: ☐ centrifugal ☐ screw ☐ pneumatic ejector ☐ grinder ☐ other (specify): _____________
Does pump operate? ☐ Yes ☐ No ☐ Unknown Is it a backup pump? ☐ Yes ☐ No
Power source for pump: ☐ electrical service ☐ combustion motor Is fuel available? ☐ Yes ☐ No
Size: _________ IN / MM Amperage:_________ AMPS Wattage: ________ WATTS
Capacity: _________ GAL/SEC or LITER/SEC Flow Rate: _________ GAL/SEC or LITER/SEC
Other Relevant Information: ____
Does pump show signs of steady leakage? ☐ Yes ☐ No If yes, give details: ______________________
Does pump generate excessive noise? ☐ Yes ☐ No If yes, give details: ______________________

Figure 10. Infrastructure Inspection Form from the First Volume of the SWEAT Book. *Source:* U.S. Army Corps of Engineers, Engineer Research and Development Center (ERDC)/. Construction Engineering Research Laboratory (CERL), ERDC/ CERL SR-07-16, *SWEAT Volume 1: Field Inspection Guide for Sewer, Water, Electric, and Telecommunication Systems (*U.S. Army Corps of Engineers, December 2007), 95.

Before continuing, it should be noted that every organization represented by Figure 11, as well as a host of other subordinate and/ or unaffiliated government and non-government organizations, maintain their own infrastructure information system as well. While on one hand it is encouraging to know that senior leaders are aware of the critical nature that CI plays within the COE, it is equally discouraging to realize that there are many redundant and/ or uncoordinated efforts in this regard. The end result being that precious time is often wasted within stability operation environments by performing repeated infrastructure reconnaissance and assessments by representatives of different organizations before something is done to fix the problem. This inefficiency not only squanders precious resources, but leads to frustration among the host nation (HN) populace as well (Kilcullen, 2007, Slide 61). With that in mind, it is important to realize that the Critical Infrastructure Portfolio Selection Model, before being fully implemented as a decision support system (DSS), must thoughtfully identify the manner in which it will populate the data of its DSS (see Chapter 3 and Appendix B for specific information related to the development of a DSS for the Critical Infrastructure Portfolio Selection Model).

Effects/ Capability-Based Planning and Systems Thinking

The third body of work that will be addressed is related to the effects- and capabilities-based, as well as "systems thinking," literature that has permeated just about every professional discipline over the past several years. Before continuing onto the body of literature itself, it is important to identify some of the organizations that have given credence to this trend.

Managing one of the largest post-conflict reconstruction efforts in history is a daunting task. Given the diplomatic and military requirements that this effort entails, it should come as no surprise that responsibility for reconstruction missions falls under the purview of both the Iraqi Reconstruction Management Office (IRMO), which is an extension of the U.S. Embassy in Iraq, and Multi-National Forces – Iraq (MNF-I), which is a Department of Defense organization. While it is IRMOs responsibility to identify reconstruction requirements and priorities, the role of managing and allocating resources has fallen to two DoD organizations that are subordinate to MNF-I: the Joint Contracting Command – Iraq/ Afghanistan (JCC – I/A) and the Gulf Region Division (GRD) of the U.S. Army Corps of Engineers (USACE) (Department of Defense, Thompson, 2007).

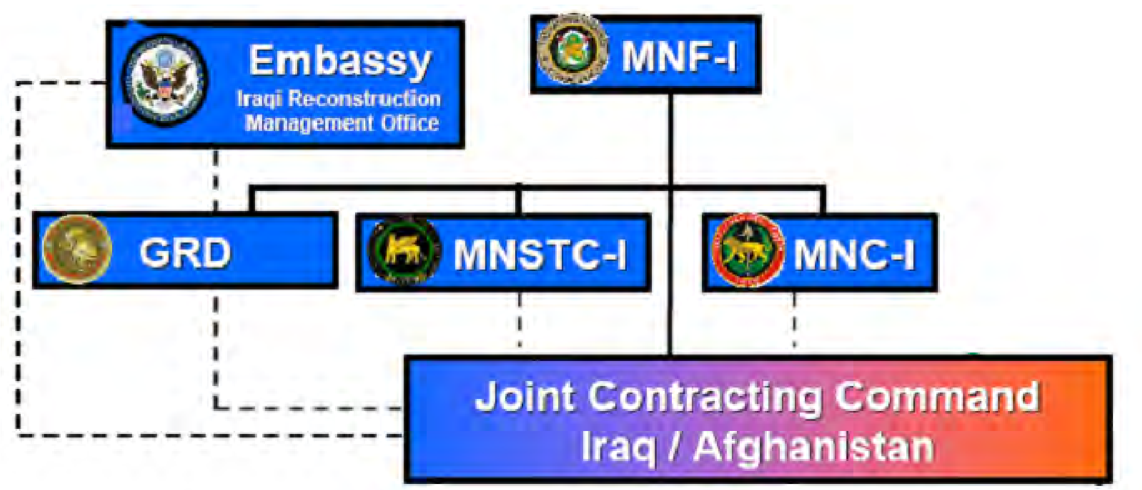


Figure 11. Organizational Chart Depicting Relationship Between IRMO (embassy), MNF-I, and the Organizations Responsible for the Management of Iraqi Reconstruction (GRD and JCC-I/A). *Source:* Thompson, *Assistance and Opportunities: Iraq –Afghanistan* (Ft. Belvoir, VA: Defense Technical Information Center (DTIC), Date of presentation not given; final version of presentation saved 31 January 2007), Slide 7.

While Figure 11 offers a simplified explanation of the Iraqi reconstruction responsibilities, it is sufficient for the purpose of this thesis. It is also important to note that the purpose of this thesis is not to offer a critique of the command structure that is responsible for managing the reconstruction of Iraq, but to recommend an alternative to the existing methodology that is used to prioritize the reconstruction effort of critical infrastructure (CI). Specifically, it appears that the majority of the reconstruction efforts in Iraq and Afghanistan have not been truly focused on yielding desired effects (i.e. "effects-based") or yielding enhanced host-nation (HN) capabilities or capacity (i.e. "capabilities-based"), nor focused on providing the greatest value at the least possible cost to the HN and the international community. Therefore, it is necessary to offer a review of the literature that was valuable in shaping the development of the Critical Infrastructure Portfolio Selection Model and the "systems-thinking" concepts that are embedded within the model.

A great place to start in understanding "systems-thinking" concepts is the Sustainability Institute's "Leverage Points: Places to Intervene in a System," by Donella Meadows. In this document, written by one of the disciples of the early pioneers of systems analysis, Dr. Jay Forrester, Meadows provides a discussion of the top twelve places to intervene in order to change the dynamics of a system, regardless of whether the system is biological, physical, economical, etc. Meadows provides ample, thoughtful examples across multiple domains in a very non-quantitative manner. However, Meadows also alludes to a powerful modeling and software tool, known as Systems Dynamics, that enables one to model complex relationships between entities in a system. More significantly for the purpose of this research is the fact that Sandia and Los Alamos

National Laboratories use this modeling software to analyze the complex relationships that exist between critical infrastructure – both in a domestic, protection role, as well as in a stability operations, reconstruction role. Also, while the Critical Infrastructure Portfolio Selection Model does not use system dynamics simulations as the basis for its fundamental structure and design, the Critical Infrastructure Portfolio Selection Model uses the results of system dynamics models, as developed by members of Sandia National Laboratories, to help justify the selection of system output measures of effectiveness (MOE) in the mathematical model (Hightower, personal conversation, 2007).

While Meadows and Forrester provide the theoretical underpinnings of systems analysis and "systems-thinking" concepts, from an applied systems analysis perspective, one of the most recent documents that fall within this larger body of literature is a paper written by Kathleen Hicks and Eric Ridge. *Planning for Stability Operations: The Use of Capabilities-based Approaches, A Report of the International Security Program Center for Strategic and International Studies (CSIS)* clearly articulates the goals of a capabilities-based approach for planning (CBP) within a stability operations environment which is to "select the right combination of inputs to achieve desired system-wide outcomes" (Hicks, 3). Hicks and Ridge provide a detailed analytic framework for CBP, to include an overview of DoD's CBP approach. Within the author's analytic framework, they provide a very useful cross-walk of various USG perspectives on stability operations missions (Figure 12).

State Department: Essential Tasks Matrix	Defense Department: StabOps Joint Operating Concept	U.S. Army: Stability Tasks Draft FM 3-0
Security	Safe & Secure Environment	Civil Security
Justice & Reconciliation		Civil Control
Governance & Participation	Representative, Effective Government	Support to Governance
Economic Stabilization & Infrastructure	Critical Infrastructure & Essential Services	Support Economic Infrastructure Development
	Economic Development	
Humanitarian Assistance & Social Well-being	Humanitarian Assistance	Provision of Essential Services

Figure 12. This Figure Offers Different (USG) Perspectives on the Stability Operations Mission Sets.
Source: Hicks, Kathleen and Eric Ridge, *Planning for Stability Operations: The Use of Capabilities-based Approaches* (Washington D.C.: Center for Strategic and International Studies (CSIS), December 2007), 6.

The significance of the near unanimity among the perspectives on stability operations (Figure 12) is relevant from the point of the Critical Infrastructure Portfolio Selection Model, since this common operating picture makes future quantitative, inter-agency planning models much more viable. Hicks and Ridge conclude the first section of their paper by stating that the "…capabilities-based approach emphasizes outcomes, measured in meeting operational needs, over inputs, typically measured in numbers and types of discrete programs or platforms" (Hicks, 9). The Critical Infrastructure Portfolio Selection Model emulates this approach since it also emphasizes outcomes, or effects, while still considering inputs (resources) required.

In an effort to demonstrate the paper's CBP assertion, the authors go on to analyze five distinct stability operations case studies: Afghanistan, Combined Joint Task Force – Horn of Africa (CJTF-HOA), East Asian Tsunami Relief, Haiti, and Kosovo. Their analysis includes the identification of three overarching environmental factors by which these scenarios can be compared for the purposes of tailoring force packages that possess the requisite stability operations capabilities. The first environmental factor is permissiveness at the point of entry and throughout operations. Hicks and Ridge go on to define permissiveness as "the level of hostility that U.S. personnel encounter during entry or at any other time during an operation" (Hicks, 11). The authors define the second environmental factor as the "level at which the U.S. government or its allies, particularly their military forces, have previously been engaged in the region" (Hicks, 12). The final environmental factor that the work's authors deem necessary for developing capabilities-based force packages is the level of surprise of the crisis to the U.S., the target population, or other key players (Hicks, 13). While Hicks and Ridge do not explicitly define this factor of surprise, they have done a good job of developing capabilities-based measures of effectiveness (MOEs) or metrics within their appendices.

Effects-based operations (EBO), like the capabilities-based planning (CBP) methodology, is just another analytical technique that has been developed to help justify the allocation of resources in order to satisfy user requirements. Since EBO is both widely discussed in DoD literature, and is similar to CBP in that it maps the allocation of resources to organizational objectives via specific, "effects-based" metrics, a detailed explanation will be omitted. It should be noted, though, that Thomas Morrell and Michael Kwinn from the United States Military Academy (USMA) developed the

Effects-Based Assessment Support System (EBASS) as an automated DSS tool which utilizes the principles of EBO to enable commanders to make better decisions within a stability operations environment (Figure 13). However, what is important to note is that while this thesis introduces the EBASS tool, most Army major subordinate commands and geographic combatant commands have developed and implemented their own EBO-based DSS to facilitate decision-making within their commands.[i] While it is commendable that senior level staffs are facilitating their commanders' decision-making ability with the use of such tools, the lack of a standard USG platform and standard measures of effectiveness, coupled with a lack of standard information-management protocols adversely impacts the development of new tools such as the Critical Infrastructure Portfolio Selection Model.

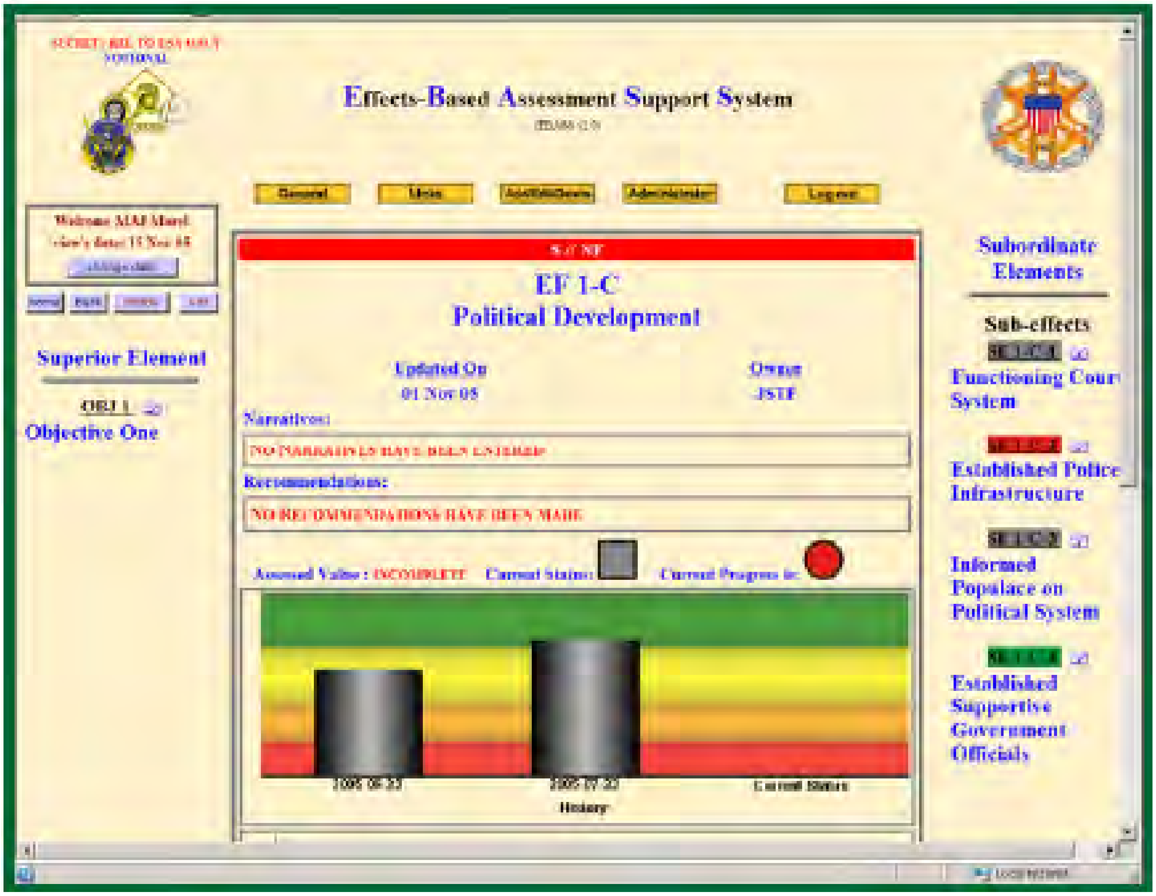


Figure 13. Screen Shot of One of the LOE Assessment Pages of the Effects-Based Assessment Support System (EBASS).

Source: Morrell, Thomas O., Earnest Y. Wong, Simon R. Goerger, Michael J. Kwinn, Jr., and Ronald C. Dodge, Jr., *Effects Based Assessment Support System (EBASS)* (West Point, NY: Operations Research Center of Excellence (ORCEN), May 2006), 31.

Finally, before concluding the section on "systems-thinking" literature and concepts that are applicable to the Critical Infrastructure Portfolio Selection Model, it is important to acknowledge an important, underlying systems concept: the system (project) lifecycle evaluation assumption. This lifecycle assumption states that before any system design, or critical infrastructure project, is undertaken, the project's entire lifecycle, from concept design to retirement, must be considered. Unfortunately, based on the majority of the literature reviewed thus far, many reconstruction projects undertaken in stability

operations environments do not account for this “cradle-to-grave” lifecycle assumption. Nor do these projects adequately consider the second- and third-order effects propagated throughout other, interdependent systems, or lines of effort, by the reconstruction project decision. Therefore, any proposed methodology, including the Critical Infrastructure Portfolio Selection Model, must account for an infrastructure component project as a “system-of-systems” whose lifecycle must account for interactions and interdependencies across multiple LOEs.

Stability, reconstruction, conflict initiation, and conflict termination

The final body of work that will be considered is the conflict initiation and termination literature. As stated previously, this final category of literature is vital, since it not only provides the context for the primary research question under investigation, but it also provides a partial, quantitatively-supported justification for the selection of measures of effectiveness (MOEs) employed by the Critical Infrastructure Portfolio Selection Model. The first category of literature that falls within this final body of literature is material that has been generated from various conferences and workshops designed to collect insights and lessons learned from stability operations subject matter experts. The second category of literature that falls within this final body of literature is material that directly impacts the development of policies related to stability and reconstruction operations. The final category is actually a more refined subset of the category mentioned previously. Specifically, the final category provides an overview of the work of world-renowned economists, Paul Collier and Anke Hoeffler, and the econometric models that these scholars have developed in an effort to explain the outbreak of conflict that often precipitate stability and reconstruction operations, as well

as the applicability of their models to the proposed Critical Infrastructure Portfolio Selection Model.

The first category of literature reviewed within this final body of literature is actually based on material taken from various workshops and conferences that have been dedicated to the further analysis of stability operations. The first piece is an out brief from a series of Stability Operations (SO) Gap Analysis Workshops that were conducted by TRAC-Leavenworth at the behest of the Army G3. The purpose of the workshops were to assemble stability operations subject matter experts (SMEs) in an effort to identify the most critical capability shortfalls with respect to the Army's ability to perform stability operations missions within a fictional, yet realistic, scenario. The output from these workshops included a prioritized list of where the Army falls short in accomplishing specific stability operations tasks, as identified within the Army Universal Task List (AUTL) (U.S. Army TRAC-Leavenworth, Stability Operations (SO) Gap Analysis Presentation, 2006). While the prioritization methodology was fairly unsophisticated, the "Gap Analysis" presentation provides a quick overview of specific stability operations tasks that the Army does either not perform well, or is not resourced adequately to complete. It is the desire of the author of this thesis that the output from the Critical Infrastructure Portfolio Selection Model can help leaders mitigate these training and resource capability "gaps" within our Armed Forces by identifying those pieces of host nation critical infrastructure that add the most "value" to the affected population, and either protecting, maintaining, or reinforcing, accordingly.

Other workshops on stability operations and reconstruction conducted by the Army's Peacekeeping and Stability Operations Institute (PKSOI) at the Army War

College, and the Office of the Secretary of Defense (OSD), have resulted in extensive amounts of metric development and assessment literature, the most relevant output being the development of the Measuring Progress in Conflict Environments (MPICE) tool. In the executive summary, it states that "The primary objective of the Measuring Progress in Conflict Environments (MPICE) program is to develop an interagency metrics analysis capability applicable to any stabilization and reconstruction environment of interest." (Peacekeeping and Stability Operations Institute (PKSOI) Workshop deliverable, Measuring Progress In Conflict Environments (MPICE): Initial Metrics Analysis Tool, December 2006, 2). The MPICE is the culmination effort of numerous government agencies, non-governmental organizations, and private think-tanks that has resulted in the development of a robust decision support system (DSS), similar to the EBASS system, mentioned in the previous section. However, while the MPICE attempts to take indicators from a host of sources and provide a strategic assessment regarding a country's potential for deteriorating into (or emerging from) a stability operations environment, the Critical Infrastructure Portfolio Selection Model has a much less ambitious goal of helping leaders prioritize the reconstruction of specific pieces of infrastructure within an affected environment.

The final reference cited within this sub-category is the USACE Gulf Region Division's (GRD) *Iraq Reconstruction Report*. Published quarterly, the April 2007 edition of this report makes a greater effort (compared to previous editions) to stress life-cycle management of reconstruction projects, as well as address "effects" induced by the reconstruction of various projects. However, one of the most useful insights gleaned from this report with respect to the Critical Infrastructure Portfolio Selection Model is the

manner in which USACE attempts to link strategic-level policy to the reconstruction, protection, and routine maintenance of critical infrastructure.

The second category of literature that falls within this final body of material directly impacts the development of policies related to stability and reconstruction operations. One of the more influential documents within this category is *Winning the Peace: An American Strategy for Post-Conflict Reconstruction*, edited by Robert C. Orr, the one-time United Nations Assistant Secretary-General for Policy Coordination and Strategic Planning. The author discusses strategic capabilities that the United States must enhance in order to effectively operate within a stability operations environment which has a fundamental objective of national reconstruction. Like the aforementioned capabilities-based planning article by Hicks and Ridge, Orr also presents a series of contemporary reconstruction case studies and most importantly, cites the ten things the U.S. can do in order to develop a more comprehensive post-conflict reconstruction strategy. Not surprisingly, Orr states that the most important thing the United States can do in this regard is to develop a prioritization framework that will help policy-makers best allocate its national resources to assisting in post-conflict reconstruction missions (Orr, 2004, 290).

A 2005 – 2006 Department of Defense and Department of State effort produced the document, *U.S. Government Draft Planning Framework for Reconstruction, Stabilization, and Conflict Transformation*, and the presentation, *Post-Conflict Reconstruction Essential Tasks*. The first document outlines a multi-criterion approach for planning and prioritizing reconstruction efforts across LOEs at the strategic level. While neither the document, nor presentation truly advocate an “Effects-based” approach,

they go a long way in facilitating the construction of good MOEs and most importantly, providing a method by which MOEs at the tactical level can be cross-walked back to goals and objectives at the strategic level. Similarly, the *Post-Conflict Reconstruction Essential Tasks* presentation provides a supporting task list which thoroughly decomposes tasks that must be accomplished across LOEs over the duration of a post-conflict reconstruction mission. The *Post-Conflict Reconstruction Essential Tasks* is particularly useful because it cites goals, by phase of the reconstruction mission, along with the tasks that must be accomplished during each phase and it is a far more comprehensive listing than what can be found in FM 3-24.

As stated previously, the final sub-category of literature to be reviewed within the final body of work is also related to policy formulation vis-à-vis stability and reconstruction operations. However, unlike the quantitative modeling efforts discussed previously (e.g. EBO, CBP, DEA, etc.), this body is dedicated to the review of econometric models that have been developed at the behest of the World Bank and United Nations by. The first article written by Collier and Hoeffler, *Greed and Grievance in Civil War*, was published in October of 2001 and focuses on analyzing factors (variables) that Collier and Hoeffler identify as precipitating the onset of civil wars and internal conflicts over the past 40 years. Collier and Hoeffler then placed these factors into two distinct categories. The first set, or "grievance," variables refer to factors "such as high inequality, a lack of political rights, or ethnic and religious divisions in society" (Greed and Grievance, Collier and Hoeffler, 1). Conversely, the term "greed" refers to factors such as "access to finance…extortion of natural resources, and…donations from a diaspora population" (Greed and Grievance, Collier and Hoeffler,

1). Collier and Hoeffler approached this problem out of an interest to determine which set of factors, "greed" or "grievance," were most significant in predicting outbreaks of violence between population groups within a single country. Since the Army Field Manual which addresses operations (FM 3-0) states that stability operations figure prominently in the event of civil war, it is only logical that U.S. military planners should consider those factors deemed to be significant within Collier and Hoeffler's econometric analysis. One of the valuable contributions that Collier and Hoeffler make to the literature is the manner in which they precisely define each of their variables and fully document the exact procedures that they use to obtain the results. This transparency of effort makes it that much easier for military planners to translate Collier and Hoeffler's efforts to action. With that in mind, Collier and Hoeffler conclude *Greed and Grievance in Civil War* by stating that the "greed," or economic, factors were consistently the most statistically significant in terms of their explanatory power regarding their ability to predict the outbreak (or cessation) of civil war (Greed and Grievance, Collier and Hoeffler, 16 – 17). The first variable that Collier and Hoeffler conclude is significant is the availability of finance, particularly from diaspora (displaced civilian) populations that immigrate to other countries, such as the Jewish, Palestinian, and Irish populations in America that have been known to finance conflicts in their countries of origin. The other significant variable that this thesis will consider is the cost of rebellion. Collier and Hoeffler then cite three specific sub-factors influencing the cost of rebellion: male, secondary education enrollment; per capita income, especially from non-primary commodity (e.g. oil, diamonds) sources; and the population growth rate. The Critical

Infrastructure Portfolio Selection Model will explicitly and implicitly account for each of these aforementioned variables, and related sub-factors.

In the next paper written by Collier and Hoeffler, *Aid, Policy and Growth in Post-Conflict Societies*, the authors attempt to apply the same econometric analysis that was used in *Greed and Grievance* to a post-conflict (e.g. unstable peace) environment in order to help formulate the most effective aid and reconstruction packages for countries in need. The most significant assertion made by Collier and Hoeffler in this paper is that post-conflict aid should increase gradually during the first three years after the conflict – as governance and economic development capacity is increasing. They go onto to state that the bulk of financial aid to countries emerging from civil war should occur after the first three years of the termination of the conflict, and taper off to original, pre-conflict levels by the end of the first decade after the conflict. While the Critical Infrastructure Portfolio Selection Model does not account for post-conflict reconstruction aid, per se, the model does account for the time intervals proposed by Collier and Hoeffler. However, Collier and Hoeffler's second paper is not without criticism. The authors have drawn the lion's share of criticism from other analysts and leaders within the world aid community, such as the United Nations, World Bank, and various non-profit organizations, who have called into question the validity of their results. Speaking to this point, a team from a Norwegian institute for development studies and human rights wrote the article *Economic Aid to Post-Conflict Countries: A Methodological Critique of Collier and Hoeffler*. While this critique does not dispute the integrity of the research performed by Collier and Hoeffler, the team does call into question the explanatory power of some of the conclusions that Collier and Hoeffler are able to draw from the

regression analyses. This is due to three primary reasons: inadequate sample sizes, coding idiosyncrasies, and the inaccessibility of a confidential data set (Suhrke, et al., 3 – 5). Despite these legitimate criticisms, though, Collier and Hoeffler have clearly provided meaningful, unprecedented modeling assistance to policy-makers in the world aid and reconstruction community; to say nothing of the fact that the implications of their analysis hold tremendous significance for the Critical Infrastructure Portfolio Selection Model.

Summary of the Literature Review

The reader can clearly observe that the literature reviewed for this thesis covers the breadth of multiple, seemingly disparate, academic and professional knowledge domains. With this in mind, it is important to articulate where the Critical Infrastructure Portfolio Selection Model seeks to expand upon the body of knowledge: quantitative methods, critical infrastructures and interdependencies, effects/ capabilities-based planning and systems thinking concepts, and the post-conflict stability and reconstruction domain.

Regarding the first, or quantitative methods, category, the Critical Infrastructure Portfolio Selection Model seeks to modify the DEA-based, portfolio-generation technique used by Eilat, et al. In this sense, the Critical Infrastructure Portfolio Selection Model is a unique application of the model proposed by Eilat, et al., which can be utilized by policy-makers in order to determine how best to provide essential services to a population trapped within a stability operations environment via the expansion, protection, and maintenance of critical infrastructure.

In the second, or critical infrastructures and interdependencies, category, the Critical Infrastructure Portfolio Selection Model seeks to exploit the U.S. domestic infrastructure protection models by considering the most efficient manner in which to rebuild, protect, or maintain infrastructure components in a stability operations environment. While this capability may not be important for the day-to-day functioning of domestic (American) critical infrastructure, this model could be applied in civil-support operations (i.e. domestic emergency) scenarios in much the same way that it should be applied in stability operations scenarios. The Critical Infrastructure Portfolio Selection Model, given its focus within a stability operations environment, is also a unique application of the “critical node analysis” methodology proposed by Dr. Ted Lewis. If implemented, the Critical Infrastructure Portfolio Selection Model’s use of the GATER (or other automated, information-based) system would also be a unique application within this domain as well.

Regarding the third, or effects/ capabilities-based planning and systems thinking concepts, category, the Critical Infrastructure Portfolio Selection Model seeks to provide a more holistic framework for addressing the problems associated with the reconstruction of critical infrastructure in a stability operations environment, than has been developed previously. Specifically, the Critical Infrastructure Portfolio Selection Model places an emphasis on accounting for four related concepts that do not appear to have been widely considered in the past prior to undertaking reconstruction projects: the infrastructure design life, infrastructure interdependencies with other infrastructure, understanding/ measuring the desired effects of the reconstruction effort over the design life of the

project, and understanding when it is better to build new infrastructure components versus protecting or maintaining existing infrastructure components.

The fourth, and final, category of literature that was reviewed fell within the post-conflict stability and reconstruction domain. It appears that there are several areas in this domain to which the Critical Infrastructure Portfolio Selection Model might contribute. First, it is evident based on the results of various studies and workshops conducted by several governmental and non-governmental "think-tanks" that there is no codified process by which these organizations can recommend the allocation of resources in support of critical infrastructure construction, protection, and maintenance in a stability operations environment, the Critical Infrastructure Portfolio Selection Model seeks to fill that void. The second area in which the Critical Infrastructure Portfolio Selection Model might contribute to the domain's body of knowledge is in providing a more practical method by which policy-makers might able to implement the infrastructure development and renewal aspects of the *U.S. Government Draft Planning Framework for Reconstruction, Stabilization, and Conflict Transformation*, and the *Post-Conflict Reconstruction Essential Tasks*, which, in turn, should facilitate improved progress along the other lines of effort (DoD) and sectors (DoS). The final area in which this thesis might contribute to the domain's body of knowledge is via the extrapolation of Collier and Hoeffler's econometric modeling results to the Critical Infrastructure Portfolio Selection Model. It should be made clear that extreme caution should be taken when attempting to extrapolate the results obtained from one data set and problem domain, to another, related but clearly non-identical domain. However, the similarities between Collier and Hoeffler's studies' scenarios, and the stability operations scenarios to which

the Critical Infrastructure Portfolio Selection Model should be applied, make the extrapolation compelling and logical.

CHAPTER 3

RESEARCH METHODOLOGY

Revisiting the Problem Definition

It is clear that civil-military planners lack a quantitative model or tool that enables them to codify the process of prioritizing the construction, protection, and/ or maintenance of critical infrastructure components within a stability operations environment. However, the need for a tool of this nature is paramount, especially in light of the 2007 Joint Operating Environment (JOE) assessment prepared by the United States Joint Forces Command's (USJFCOM):

> The U.S. may be drawn more frequently into these [stability operations environment] situations, either alone or with allies, to help provide stability before conditions worsen and are exploited by extremists (USJFCOM, Joint Operating Environment: Trends and Challenges for the Future Joint Force through 2030, 11).

Furthermore, it is hoped that one of the additional benefits associated with using such a tool would be to enable civil-military planners to serve as better stewards of the taxpayers' resources. Therefore, the ultimate purpose of this research methodology is to outline the approach that will ultimately facilitate the successful integration and implementation of the Critical Infrastructure Portfolio Selection Model (see Figure 14, Phases V and VI). However, the more immediate focus of this thesis, and this chapter in particular, is to provide a brief overview of how the Critical Infrastructure Portfolio Selection Model requirements were derived (Figure 14, Phase I), and how these requirements translate to a system concept (Figure 14, Phase II) that is introduced within this chapter via a mathematical model.

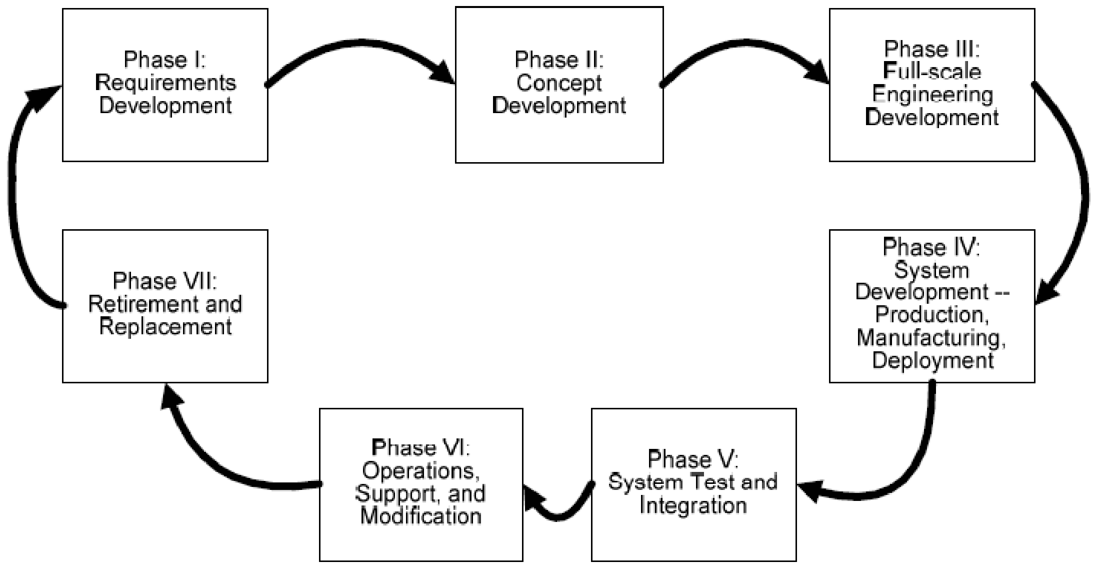


Figure 14. System Design Life Cycle as Explained by Dr. A. Terry Bahill, Department of Systems and Industrial Engineering, University of Arizona.

Requirements Development and Needs Analysis

Before delving into the mathematical model and data management layers which undergird the Critical Infrastructure Portfolio Selection Model, it is necessary to provide an overview of several system requirements that have been identified thus far. It is important to note that by providing the overview of system requirements, the general methodology of the Critical Infrastructure Portfolio Selection Model will be made apparent. It should also be noted that any alternative design of the Critical Infrastructure Portfolio Selection Model should account for how well the design satisfies the following significant requirements: system life cycle considerations; identification of appropriate input and output metrics; and the method of determining the probability of project "success."

The first requirement that would need to be addressed in more depth is the need to ensure that the Critical Infrastructure Portfolio Selection Model accounted for individual critical infrastructure component project input and output parameter values (i.e. metrics) over the life cycle of the infrastructure component (see Figure 14). For instance, while it may be important for an infrastructure project such as a water treatment plant to serve as large of a population as possible, the relative importance of the number of people served may shift over time based on the decision-maker's needs. As an example, consider the decision-maker who has a fundamental decision to make: is it more important to get a particular infrastructure project up and running immediately in order to serve 1000 people in an affected area, or is it preferable to invest more heavily in the infrastructure component and serve ten times that number of people? Or can the same effects be achieved over time by simply investing a relatively modest amount of money to protect and/ or maintain the existing infrastructure component? In any event, planners must understand both the short and long-term implications associated with their decisions in a particular stability operations scenario. In order to account for this system life cycle requirement, all output MOEs have adopted the convention of using a weighted average of a particular unit of interest per unit of time over the anticipated lifecycle of the infrastructure component. The first MOE, associated with the number of people served by a particular infrastructure project, epitomizes this important life cycle requirement:

> MOE/ Output 1: *Weighted average of the number of people served by infrastructure project per month over the lifecycle of the infrastructure component*.

MOE/ Output 1 *(restated)*: *Weighted average of the number of people served by infrastructure project* [unit of interest = number of people served by a particular infrastructure project] *per month* [unit of time = month] *over the lifecycle of the infrastructure component* [the lifecycle (in most instances) = operational design life of project; this is the amount of time that the infrastructure project is providing a meaningful output].

Furthermore, it should be noted that the weight (or importance) associated with each time interval of the MOE will be dictated by the decision-maker based upon input from the staff and other pertinent stakeholders. For example, the decision-maker may consider it most important that the critical infrastructure project delivers the maximum level of service during the first time interval, thereby assigning the MOE for the first time interval a weight of 0.70 (seventy percent out of one hundred percent possible); whereby the remaining two time intervals under consideration get weights of twenty and ten percent, respectively. Of course, as the renowned COIN expert, David Kilcullen, has stated, "immediate programs are necessary, but [they] have to be set up so as not to undermine long-term objectives" (Kilcullen, 2007, Slide 60). Hence, decision-makers must carefully consider whether or not they should heavily weight the initial effects of every infrastructure project in every instance.

The second requirement that the Critical Infrastructure Portfolio Selection Model would need to address was ensuring that appropriate input and output metrics were identified. Regarding input metrics, Colonel Timothy Trainor and Lieutenant Colonel Dale Henderson, two professors from the Department of Systems Engineering at West Point, during a recent trip to work with infrastructure ministry officials in Basrah, Iraq, realized that the most reasonable type of input in a reconstruction scenario, must somehow be tied the capacity of a country, province, or city to govern itself (Henderson,

2007). This realization, in turn, led to the conclusion that budget amounts are the most reasonable way to measure the allocation of resources towards the construction, protection, and maintenance of critical infrastructure, while simultaneously facilitating governance capacity.

Similarly, the next issue to resolve was the manner in which reasonable output metrics would be determined. According to Parnell, et al. a good measure of effectiveness (MOE) (Parnell, et al., 2008, 99):

- Reflects and measures functional objectives of the system;
- Is simple and quantifiable;
- Measures effectiveness at echelons above the system (how it contributes);
- Involves aggregation of data;
- Can be used to determine synergistic effects of a system;

Furthermore, based upon Henderson and Trainor's visit to Basrah, as well as feedback from the British Provincial Reconstruction Team (PRT), the output measures of effectiveness (MOEs) must certainly account for the number of people served – a standard measure in engineering practice for determining levels of service for essential services. The Iraqi ministry officials were also adamant that infrastructure projects somehow account for the number of people that would be employed during the construction, and operation, of the infrastructure project. While not necessarily a measure of effectiveness that would be deemed appropriate by western standards due to its propensity to reward "inefficient" projects, it is not out of the norm for countries emerging from instability to value this measure.

The remaining two measures of effectiveness under consideration for use within the Critical Infrastructure Portfolio Selection Model came from Collier and Hoeffler's

literature. The first MOE drawn from Collier and Hoeffler, and the third MOE, overall, relates to the need to ensure that the construction of infrastructure helps to prevent the displacement of civilians from the affected area. This is due to the fact that in their analysis, Collier and Hoeffler found that diaspora (displaced civilian) populations contribute largely to the availability of finance to warring factions, usually after their re-settlement in a foreign country, thereby prolonging the conflict in their country of origin (Collier and Hoeffler, 2001, 16), while simultaneously contributing to indigenous "brain drain," thereby depleting an affected country of its intellectual capital that it will surely need to help rebuild itself. The second MOE drawn from Collier and Hoeffler, and the fourth overall, relates to the need to ensure that the construction of infrastructure helps to provide a secular, secondary education-system to the affected populace. This is due to the fact that in their analysis, Collier and Hoeffler found that one of the factors that made civil-war financially viable was to ensure that the young male population was not educated, since the opportunity costs for young, uneducated males are inherently low (i.e. poor, young, and uneducated males don't have many other attractive job opportunities other than to fight one another) (Collier and Hoeffler, 2001, 16). Therefore, the final MOE relates to the need to ensure that the construction of infrastructure supports the secular secondary education of the school-aged population.

The third and final, major requirement that the Critical Infrastructure Portfolio Selection Model needed to address was to develop a method for determining the probability of project "success." While the notion of project "success" falls under the broader heading of project risk, a more thorough explanation is required. Quite simply, the probability of project "success," within the context of this thesis, refers to an

infrastructure component's ability to withstand various failure modes, and its ability to deliver its level of service, or output, to the target population, over the duration of the project's design life. While the various failure modes will be discussed in subsequent paragraphs, it should be noted that an infrastructure project's level of service is measured by the aforementioned MOEs (e.g. Average number of people served). It should also be noted that the concept of project "success" is embedded into the framework of Eilat, et al.'s DEA-based portfolio generation model, which forms the mathematical foundation of the Critical Infrastructure Portfolio Selection Model. However, since Dr. Lewis' definition of infrastructure component "vulnerability" is more mathematically precise and easier to explain to decision-makers, his convention will be used throughout this paper in lieu of the more general definition used by Eilat, et al.

Before an understanding of project "success" can be obtained, though, it is necessary to understand how an infrastructure project might possibly fail. Therefore, consider the infrastructure component that can fail due to one or more of the following, independent events occurring: terrorist attack, mechanical failure, or the failure of another infrastructure component upon which the project under consideration is dependent upon. As long as the component can fail if any of the individual failure modes occur, then the vulnerability of the project, which is the mathematical complement of the probability of project "success," can be modeled using the "OR-tree" that is shown in Figures 15. If, however, a project can fail only if multiple failure modes are acting in concert with one another (e.g. the project under consideration only fails if both terrorist attack and mechanical failure occur), then the vulnerability of the project can be modeled using the "AND-tree" that is shown in Figure 16. While this thesis will tend to focus its

examples on the more vulnerable "OR-tree" risk scenarios, it should be noted that in modern societies, where stability operations are less likely to occur, the vulnerability posed to infrastructure tends to occur from a combination of "OR-trees" and "AND-trees."

At this point, it is also important to acknowledge the relationship between failure modes and budget (input) quantities. For instance, assume that a terrorist attack (e.g. via an explosive device) is one particular failure mode for a piece of critical infrastructure. It is only logical that one should be able to "buy down" or reduce the probability that this type of failure mode occurs by simply investing more in that particular component's "protection budget," such as by building a better fence or hiring more security guards. Furthermore, while it is beyond the scope of this thesis to establish mathematical relationships between input amounts and failure modes, planners utilizing this version of the Critical Infrastructure Portfolio Selection Model should be able to subjectively assess probabilities of success/ failure based on increases/ decreases in funding levels (inputs). That is to say, a planner should be able to subjectively assess an appropriate degradation of project success, as a percentage, if he or she chooses not to invest in all of the security measures required to adequately protect a facility at the recommended level. In this sense, the planner must attempt to quantifiably assess the trade-off between decreasing cost and the anticipated decrease in the level of protection. Additionally, a more precise description of the terms utilized to calculate the probability of project success can be found within the mathematical modeling section of this chapter.

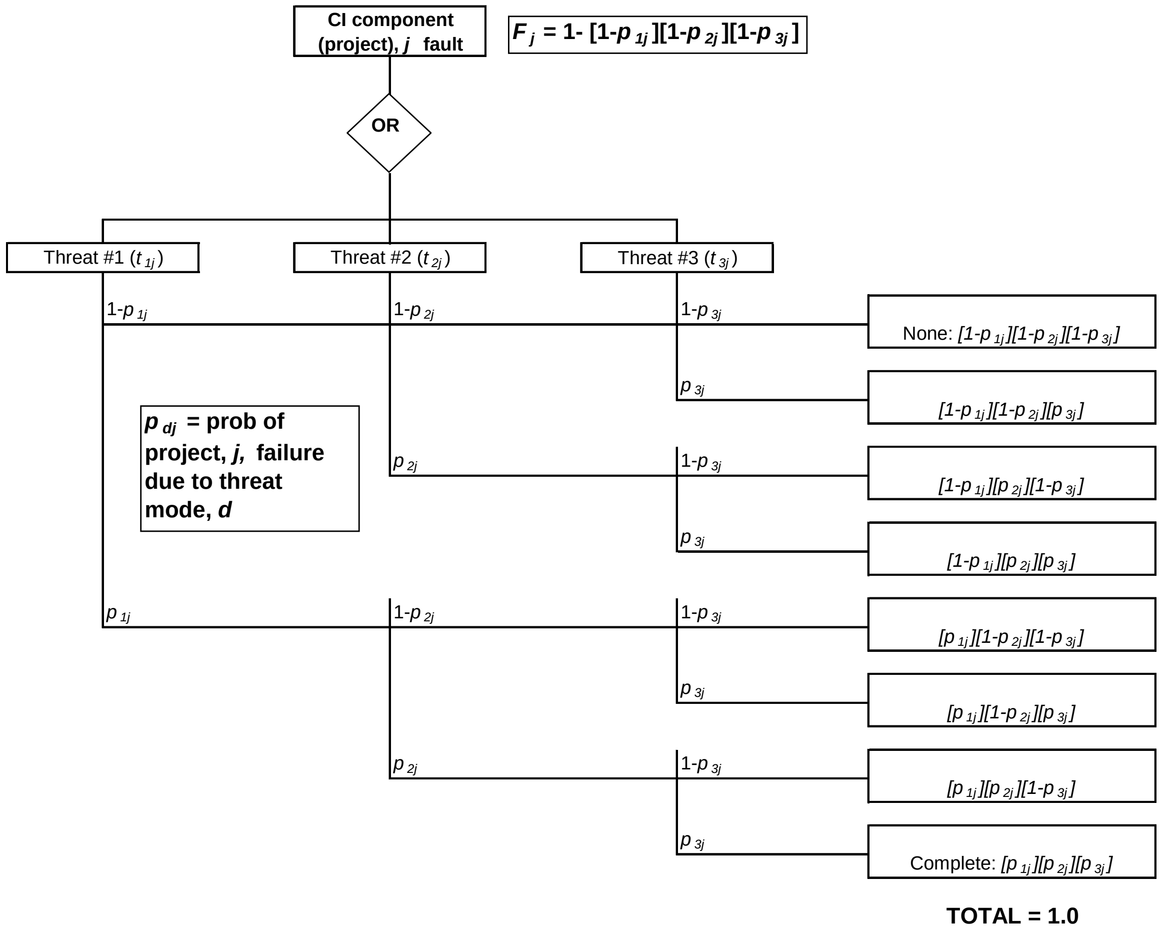


Figure 15. Complete Event Tree for a Particular Critical Infrastructure Project, Consisting of Three Possible Threat (Failure) Modes.

Note: The probability of failure for the project Fj is the complement of the first outcome (upper right hand side) indicated.

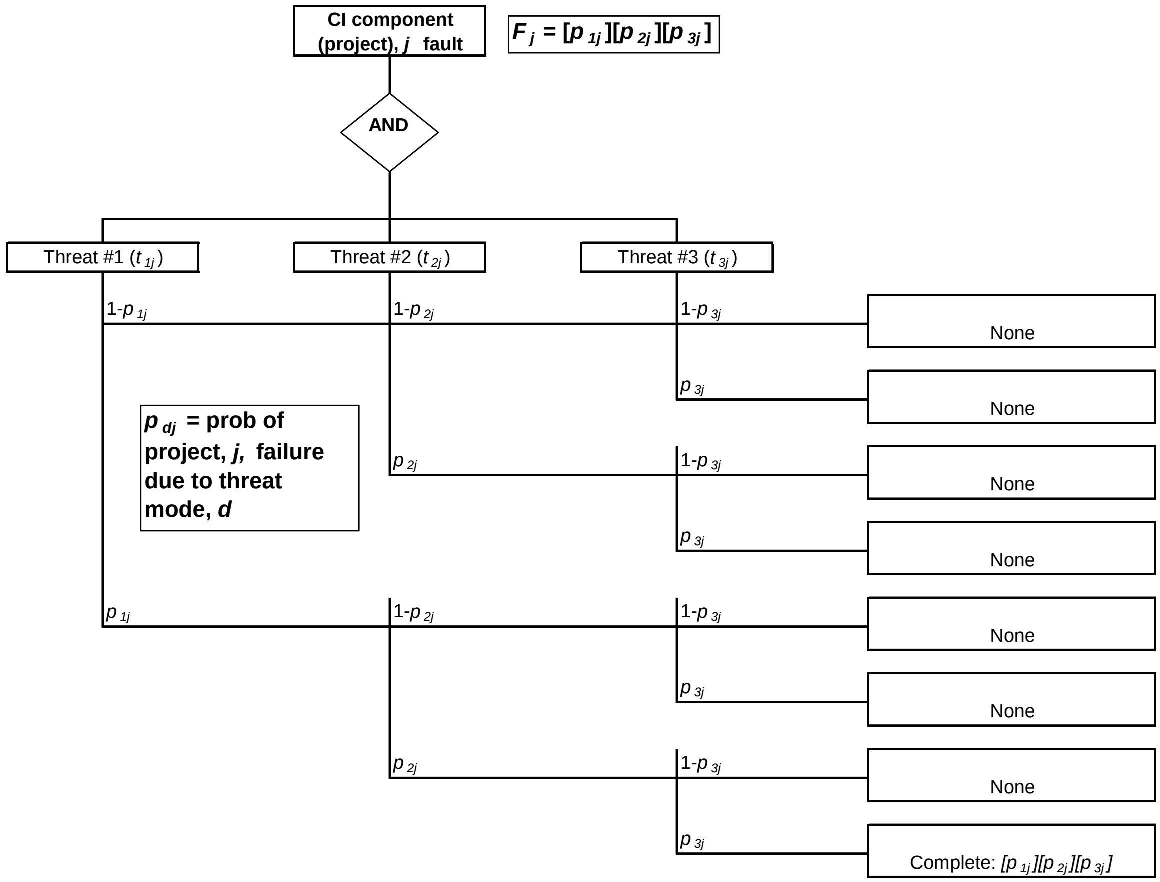


Figure 16. The Complete Event Tree (AND-Tree) for a Particular Critical Infrastructure Project, Consisting of Three Possible Threat (Failure) Modes.
Note: The only possible means of failure in this particular example is if all three threat modes occur in conjunction with one another.

Given that an exhaustive explanation of the Critical Infrastructure Portfolio Selection Model system requirements exceeds the scope of this thesis, the interested reader should review the various technical reports and presentations prepared by Corbin, et al. over the course of the 2006 – 2007 academic year. Access to the aforementioned technical report, as well as other, related USMA undergraduate and faculty technical reports can be obtained by contacting USMA's Operations Research Center of Excellence (ORCEN) (Corbin, et. al., 2007). Additionally, for a more comprehensive

background on the formal documentation associated with generating system requirements, the interested reader is directed to review any of the numerous references cited on Dr. A. Terry Bahill's website at the University of Arizona. Finally, for the authoritative guide on system life cycles, the interested reader should review the Institute of Electrical and Electronics Engineers (IEEE) 15288: The Adoption of International Organization for Standardization (ISO)/ International Electrotechnical Commission (IEC) 15288: 2002, by the IEEE Computer Society.

Methodology Overview

Having concluded a discussion of the three fundamental requirements of the Critical Infrastructure Portfolio Selection Model, it is now necessary to take a look at how the various pieces of the model will fit together within the construct of the DEA-based approach in order to provide meaningful analytical results for the decision-maker. In order to facilitate this, Figure 17 attempts to portray a graphical representation of the general overview of the methodology.

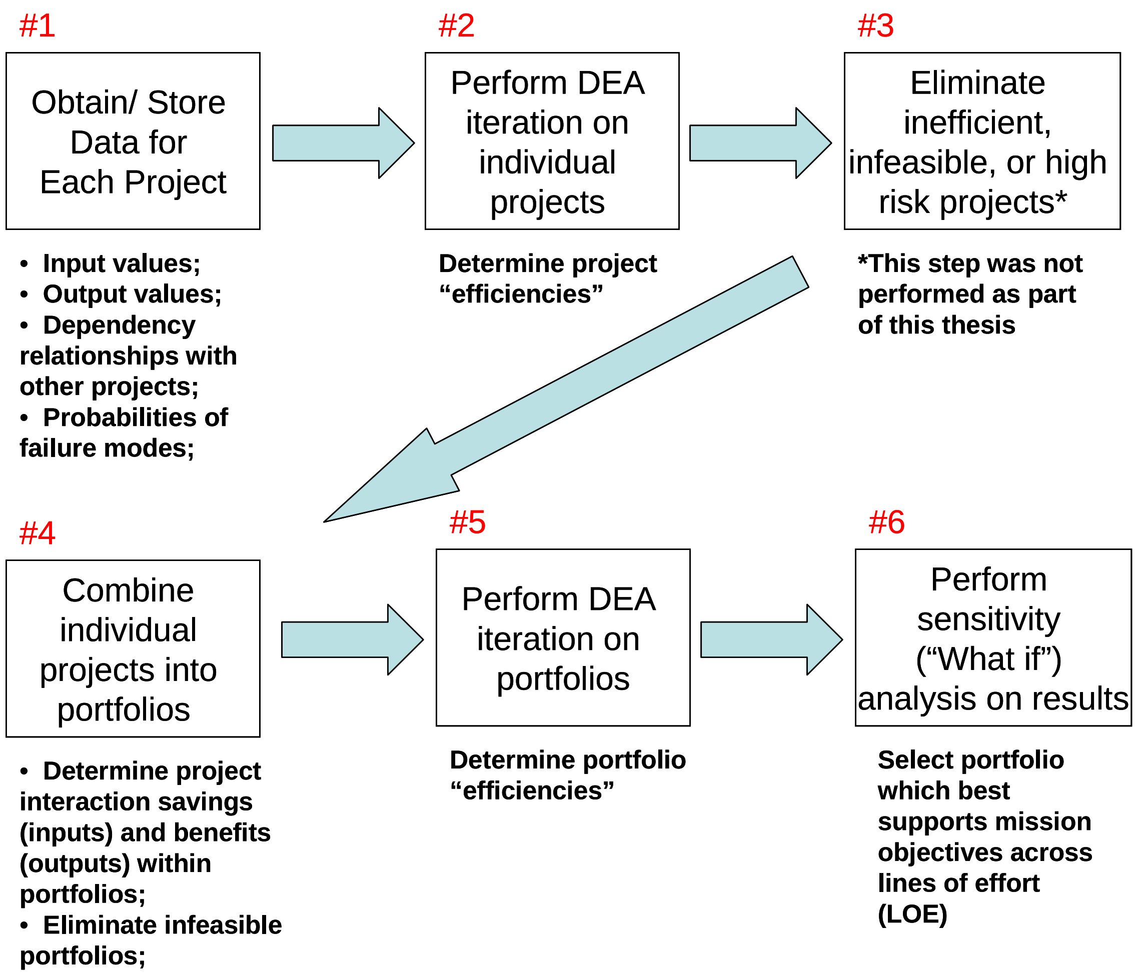


Figure 17. Overview of the Major Steps Contained within the Critical Infrastructure Portfolio Selection Model.

Figure 18 attempts to show how the raw data values appear within the spreadsheet version of the Critical Infrastructure Portfolio Selection Model. It should be noted that while units of measure and mathematical symbology have been omitted from this overview section, each of these areas will be addressed within the following, mathematical modeling, section of this chapter. However, a general form of the DEA model formulation is presented in Figures 19 and 20 in order to allow the reader to gain a

better appreciation of how the data values shown in Figure 18, will ultimately be used to help prioritize infrastructure projects, and subsequently, portfolios.

	Infrastructure Project	Input			Output				Probability of success of project
		#1	#2	#3	#1	#2	#3	#4	
1	electricity generating plant	50	30	25	20	80	5	25	0.75
2	water pumping station	10	30	15	30	15	15	40	0.85
3	children's hospital	25	15	30	50	100	10	0	0.5

Figure 18. Sample Data for Three Distinct Infrastructure Projects Used by the Critical Infrastructure Portfolio Selection Model.

However, before continuing, and in order to provide greater clarity, it should be noted that the "DEA efficiency" of a particular project, or portfolio of projects, is determined by performing the calculations shown in the mathematical models shown in Figure 19 and 20 (they are, in fact, the same model, as this will be explained later). Clearly, one can see that the objective of this model (Figure 19) is to maximize ("max") the ratio of outputs to inputs for a particular project (*j*). This simply means that it is desirable to have large weighted output, or measure of effectiveness, values, and small weighted input, or budget, values. This objective is necessarily subject to ("s.t.") the constraints that the ratios of all of the projects must be less than or equal to one, since no project can be more than 100% "efficient" with respect to the manner in which the project is able to transforms inputs (budgeted amounts) to outputs (the MOEs stated previously).

$$
\begin{aligned}
\max_{u,v} \quad & \frac{\sum_r \mu_r y_{ro}}{\sum_i v_i x_{io}} \\
\text{s.t.} \quad & \frac{\sum_i \mu_i y_{ij}}{\sum_i v_i x_{ij}} \leqslant 1 \quad \forall j, \\
& \mu_r \geqslant \varepsilon, \\
& v_i \geqslant \varepsilon.
\end{aligned}
$$

Figure 19. Non-Linear Form of the DEA Mathematical Model.
Source: Eilat, et al, *Constructing and Evaluating Balanced Portfolios of R&D Projects with Interactions: A DEA Based Methodology* (Amsterdam: Elsevier Science Publishers, 28 January 2005), 1022.

However, it should be noted that since the ratio equations in the mathematical model shown in Figure 19 do not take the general form of a line, $y = mx + b$, the model is non-linear and cannot be solved as a linear program. Therefore, it is necessary to linearize this form before it can be implemented within the Critical Infrastructure Portfolio Selection Model. This is achieved simply by transforming it in the following manner (Figure 20). The value of the transformation is that an MS Excel© spreadsheet (or other application) can now solve this as a simple linear program. Note once again that the decision-maker is primarily concerned with the outputs, or benefits, received by the affected population of the model. Hence, the terms associated with the outputs are the terms that the objective function seeks to maximize (“max”).

$$
\begin{aligned}
&Max \quad \sum_r \mu_r y_{ro} \\
&st \quad \sum_i \mu_i y_{ij} - \sum_i \nu_i x_{ij} \le 0 \qquad \forall\, j \\
&\qquad \sum_i \nu_i x_{ij} = 1 \qquad \forall j \\
&\qquad \mu, \nu \ge 0
\end{aligned}
$$

Figure 20. Linearized Form of the DEA Mathematical Model Shown in Figure 19.

Having addressed the fundamental mathematical structure that enables the Critical Infrastructure Portfolio Selection Model to generate "DEA efficiency" scores for individual projects and portfolios, it is now time to address what constitutes acceptable thresholds for project efficiency and probability of success (see Step 3 in Figure 17). In a real world application, it would be up to the decision-maker to determine whether a project satisfies initial thresholds of "DEA efficiency" and "probability of success" to be considered for inclusion within the second, portfolio selection, DEA iteration (see Steps 4 and 5 in Figure 17). However, for the sake of this example, given the small sample size of projects, n_p = 3, and the fact that all three projects are 100% efficient by DEA standards (see Figure 21), let us assume that each of the three projects will be considered for inclusion in the second, portfolio selection, phase of the modeling process. With this in mind, in reality, the commander might not want to consider the children's hospital further until he or she identifies a way to mitigate the risk that appears to be inherent in that project.

	Infrastructure Project	DEA Efficiency	Probability of success of project
1	electricity generating plant	1.00	0.75
2	water pumping station	1.00	0.85
3	children's hospital	1.00	0.5

Figure 21. Example After First DEA Iteration, Individual Project Comparison.

As stated previously, the purpose of running the DEA model a second time is to provide a prioritized list of portfolios of projects, as opposed to a prioritized list of individual projects. However, prior to performing a second iteration of the model, it is important to account for any resource (input) constraints that will limit our ability to select all of the projects under consideration. For the purpose of this example, consider that the decision-maker has at his or her disposal: $60,000 for new construction projects (i.e. Input #1), $75,000 to spend on security/ protection on these projects for the coming year (i.e. Input #2), and $50,000 to spend on the routine operations and maintenance (O&M) (i.e. Input #3) for the coming year. Furthermore, assume that decision-makers will run the Critical Infrastructure Portfolio Selection Model once a year as part of the annual budget cycle in order to assist them in selecting the best group of projects to allocate dollars towards in the coming year. Clearly, given the cost data for each of the three projects shown in Figure 18, all three projects cannot be undertaken during the current budget cycle, since the total inputs required to undertake all three projects equals $85,000, and there is only $60,000 available in new construction, Input #1, for the upcoming year. In order to facilitate a better understanding of how these constraints are imposed upon the portfolios,

please refer to Figures 22 through 24, where each figure corresponds to a different input constraint requirement, with infeasible portfolios shaded in red.

	Electricity generating plant	Water Pumping Station	Children's Hospital				x-hat		Input #1 avail (new construction)
1	1	0	0	50	10	25	50	<=	60
2	0	1	0	50	10	25	10	<=	60
3	0	0	1	50	10	25	25	<=	60
4	1	1	0	50	10	25	60	<=	60
5	1	0	1	50	10	25	75	>	60
6	0	1	1	50	10	25	35	<=	60
7	1	1	1	50	10	25	85	>	60

Figure 22. Feasible (Unshaded) and Infeasible (Shaded) Portfolios for the Resource (New Construction, Input #1) Constraint.

Note: The term "*x-hat*" represents the symbol $\hat{x}_{ik}$, which is the cumulative amount of a particular resource (input) consumed by each of the seven possible portfolios.

	Electricity generating plant	Water Pumping Station	Children's Hospital				x-hat		Input #2 avail (security/ protection)
1	1	0	0	30	30	15	30	<=	75
2	0	1	0	30	30	15	30	<=	75
3	0	0	1	30	30	15	15	<=	75
4	1	1	0	30	30	15	60	<=	75
5	1	0	1	30	30	15	45	<=	75
6	0	1	1	30	30	15	45	<=	75
7	1	1	1	30	30	15	75	<=	75

Figure 23. Feasible Portfolios for the Resource (Ssecurity/ Protection, Input #2) Constraint.
Note: None of the portfolios violate this resource availability constraint.

	Electricity generating plant	Water Pumping Station	Children's Hospital				x-hat		Input #3 avail (O&M)
1	1	0	0	25	15	30	25	<=	50
2	0	1	0	25	15	30	15	<=	50
3	0	0	1	25	15	30	30	<=	50
4	1	1	0	25	15	30	40	<=	50
5	1	0	1	25	15	30	55	>	50
6	0	1	1	25	15	30	45	<=	50
7	1	1	1	25	15	30	70	>	50

Figure 24. Feasible (Unshaded) and Infeasible (Shaded) Portfolios for the Resource (O&M, Input #3) Constraint.

Having completed an analysis of the inputs of the portfolios, it is now necessary to conduct a similar analysis of the outputs prior to re-running the DEA model. Unlike the inputs, there is no corresponding set of constraints for the outputs. However, the limiting factor with respect to the outputs becomes the inherent risk, or probability of success, of the portfolios. As was noted earlier, this probability of success information is listed in Figures 18 and 21 and is incorporated into each of the various MOE (output) calculations shown in Figures 25 through 28. Furthermore, precise definitions of each of the MOEs are listed below, as well.

	Electricity generating plant	Water Pumping Station	Children's Hospital	Expected benefits			Prob. Of success				y-hat (Output #1, Avg # people served)
1	1	0	0	20	30	50	0.75	0.85	0.5	=	15
2	0	1	0	20	30	50	0.75	0.85	0.5	=	25.5
3	0	0	1	20	30	50	0.75	0.85	0.5	=	25
4	1	1	0	20	30	50	0.75	0.85	0.5	=	40.5
5	1	0	1	20	30	50	0.75	0.85	0.5	=	40
6	0	1	1	20	30	50	0.75	0.85	0.5	=	50.5
7	1	1	1	20	30	50	0.75	0.85	0.5	=	65.5

Figure 25. Portfolio Results for Output #1 (*Weighted Average of the Number of People Served by Infrastructure Project per Month over the Lifecycle of the Infrastructure Component*).

Note: The term "*y-hat*" represents the symbol $\hat{y}_{rk}$, which is the cumulative amount of a particular benefit (output) produced by each of the seven possible portfolios.

	Electricity generating plant	Water Pumping Station	Children's Hospital	Expected benefits			Prob. Of success				y-hat (Output #2, Avg # people employed)
1	1	0	0	80	15	100	0.75	0.85	0.5	=	60
2	0	1	0	80	15	100	0.75	0.85	0.5	=	12.75
3	0	0	1	80	15	100	0.75	0.85	0.5	=	50
4	1	1	0	80	15	100	0.75	0.85	0.5	=	72.75
5	1	0	1	80	15	100	0.75	0.85	0.5	=	110
6	0	1	1	80	15	100	0.75	0.85	0.5	=	62.75
7	1	1	1	80	15	100	0.75	0.85	0.5	=	122.75

Figure 26. Portfolio Results for Output #2 (*Weighted Average of the Number of People Employed Over the Lifecycle of the Infrastructure Component*).

	Electricity generating plant	Water Pumping Station	Children's Hospital	Expected benefits			Prob. Of success				y-hat (Output #3, Avg # of displaced civilians prevented)
1	1	0	0	5	15	10	0.75	0.85	0.5	=	3.75
2	0	1	0	5	15	10	0.75	0.85	0.5	=	12.75
3	0	0	1	5	15	10	0.75	0.85	0.5	=	5
4	1	1	0	5	15	10	0.75	0.85	0.5	=	16.5
5	1	0	1	5	15	10	0.75	0.85	0.5	=	8.75
6	0	1	1	5	15	10	0.75	0.85	0.5	=	17.75
7	1	1	1	5	15	10	0.75	0.85	0.5	=	21.5

Figure 27. Portfolio Results for Output #3 (*Weighted Average of the Number of Displaced Civilians that will be Prevented over the Lifecycle of the Infrastructure Component*).

	Electricity generating plant	Water Pumping Station	Children's Hospital	Expected benefits			Prob. Of success				y-hat (Output #4, Avg # of people with access to secular secondary education)
1	1	0	0	25	40	0	0.75	0.85	0.5	=	18.75
2	0	1	0	25	40	0	0.75	0.85	0.5	=	34
3	0	0	1	25	40	0	0.75	0.85	0.5	=	0
4	1	1	0	25	40	0	0.75	0.85	0.5	=	52.75
5	1	0	1	25	40	0	0.75	0.85	0.5	=	18.75
6	0	1	1	25	40	0	0.75	0.85	0.5	=	34
7	1	1	1	25	40	0	0.75	0.85	0.5	=	52.75

Figure 28. Portfolio Results for Output #4 (*Weighted Average of the Number of People that will have Access to a Modern, Secular Secondary Education over the Lifecycle of the Infrastructure Component*).

Having completed both sets of input and output calculations for the portfolios, it is necessary to display the portfolio information in a consolidated format, along with their respective DEA efficiency scores that were generated after the input and output values were obtained (see Figure 29).

Portfolio	Input #1	Input #2	Input #3	Input Weight	Output #1	Output #2	Output #3	Output #4	Output Weight	Weighted Difference	DEA Efficiency
1	50	30	25	0.4736	15	60	4	19	0.4736	0.00	1.00
2	10	30	15	0.1656	26	13	13	34	0.1656	0.00	1.00
3	25	15	30	0.3608	25	50	5	0	0.3608	0.00	1.00
4	60	60	40	0.6392	41	73	17	53	0.6392	0.00	1.00
5	75	45	55	0.8344	40	110	9	19	0.8344	0.00	1.00
6	35	45	45	0.5264	51	63	18	34	0.5264	0.00	1.00
7	85	75	70	1	66	123	22	53	1	0.00	1.00

Figure 29. Final Results for all Portfolios.
Note: Infeasible Portfolios, Due to Violations of Resource Availability Constraints, Shaded.

It should be noted that the DEA efficiency for portfolios will not normally be 100%, or 1.00, for every project or portfolio (see Figure 29), as was the case in this example. However, a small population of projects and portfolios, coupled with a relatively small range of data values across projects within this toy model, made the manipulation of weights via the linear programming solver in Excel very simple. Nevertheless, it is hoped that the reader was able to obtain a greater appreciation for the manner in which one might use the Critical Infrastructure Portfolio Selection Model in order to incorporate input and output parameter values for individual projects, as well as portfolios, within a DEA model in order to provide meaningful decision-support to decision-makers in a stability operations environment.

Developing the Mathematical Model

The following method of conveying the mathematical construct of the Critical Infrastructure Portfolio Selection Model represents a combination of techniques borrowed primarily from LTC Dale Henderson, and an article written by the Naval Postgraduate School's Gerald G. Brown, that appeared in the December 2004 edition of

Phalanx magazine. The purpose of the mathematical modeling convention used within this section is to define the notation in a sequential and logical manner, so that terms are defined prior to commencing the discussion of the objective value and constraint functions. Furthermore, it should be noted that in most instances, the variable names are taken directly from the article written by Eilat, et al., "Constructing and evaluating balanced portfolios of R&D projects with interactions: A DEA based methodology." However, when it comes to defining probabilities of success and failure modes, the names and definitions are a modified form of what is presented within the Lewis text, *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation*.

Define the following notation:

1. Sets (including corresponding indices):
    a. The group of all candidate reconstruction-related projects or missions (G).
        i. The set of all possible projects, G, indexed by j.
        ii. The cardinality (or maximum value) of $G = |n_p|$, where n_p is the total number of projects that may be undertaken.
        iii. An example set of candidate projects, G = {electricity generating plant, water pumping station, children's hospital}; where $j = 1$ = electricity generating plant, $j = 2$ = water pumping station, etc. and $n_p = 3$.

b. A group of projects, Q, within a particular portfolio, k, or (Q_k).

i. Since Q_k is a subset of the set of all possible projects, G (i.e. $Q_k \subset G$), an example set of projects within a particular portfolio, k, includes Q_k = {water pumping station, children's hospital}.

ii. The set of all possible portfolios, Q, is indexed by k. Using the preceding example, the possible portfolios include: 1) all three projects, let this be k (portfolio) = 1; 2) the first and the third projects, $k = 2$; 3) the first and the second projects, $k = 3$; 4) the second and the third projects, $k = 4$; 5) the first project only, $k = 5$; 6) the second project only, $k = 6$; or 7) the third project only, $k = 7$. Therefore, the maximum value of k in this example is seven. However, in accordance with the preceding example, $Q_k = Q_4$ since the fourth combination of projects {water pumping station and children's hospital) was selected.

iii. Using vector notation, the aforementioned portfolios will be indicated using the vector, z_k : 1) $z_1 = \{1,1,1\}$, 2) $z_2 = \{1,0,1\}$, 3) $z_3 = \{1,1,0\}$, 4) $z_4 = \{0,1,1\}$, 5) $z_5 = \{1,0,0\}$, 6) $z_6 = \{0,1,0\}$, and 7) $z_7 = \{0,0,1\}$. Therefore, the proper vector notation for the fourth portfolio is $z_4 = \{0,1,1\}$, which is equivalent to Q_4 = {water pumping station, children's hospital}.

c. The set of all inputs (or resources) available (*M*) to invest in one or more projects, *j*, contained within set, *G*.

   i. The set of all inputs, *M*, indexed by *i*.

   ii. The cardinality of $M = |m|$.

   iii. For the purpose of this thesis, the inputs, *i*, under consideration include categories that are typically contained within a municipal, or other government, budget.

   iv. The three categories of inputs include: The amount of capital budget/ new construction dollars, a one time cost ($i = 1$, aka *new construction*), the average amount of security/ protection dollars per year over the life cycle of the project ($i = 2$, aka *security*), and the average amount of operations and maintenance dollars per year over the life cycle of the project ($i = 3$, aka *O & M*). Therefore, $m = 3$.

   v. While inputs within this thesis are monetary in nature (i.e. budget line items), non-monetary inputs such as military units or related assets could, and should, be considered for inclusion as inputs within the Critical Infrastructure Portfolio Selection Model. The rationale for selecting budget categories was initially driven by the need of the Basrah Water Directorate to establish a relationship between infrastructure reconstruction priorities and an operational budget.

   vi. See Figure 30 for summarized list of input parameters.

d. The set of all outputs (or benefits) yielded (*S*) by investing in one or more projects, *j*, contained within set, *G*.

   i. The set of all outputs, *S*, indexed by *r*.

   ii. The cardinality of $S = |s|$.

   iii. For the purpose of this thesis, the outputs, *r*, under consideration are tied closely to the factors identified by Collier and Hoeffler as being the most likely to prevent the occurrence, or re-emergence, of civil war in developing nations (see Chapter 2).

   iv. For the purpose of this thesis, the outputs, *r*, under consideration include the categories that were identified within the previous chapter: $r = 1$ = Weighted average of the number of people served by infrastructure project per month over the lifecycle of the infrastructure component; $r = 2$ = Weighted average of the number of people employed over the lifecycle of the infrastructure component; $r = 3$ = Weighted average of the number of displaced civilians that will be prevented over the lifecycle of the infrastructure component; $r = 4$ = Weighted average of the number of people that will have access to a modern, secular secondary education over the lifecycle of the infrastructure component.

   v. See Figure 30 for a summarized list of output parameters.

Input	Description	Short Name	Mathematical Symbol
#1	The amount of capital budget/ new construction dollars *(a one time cost)*	New Construction	x_{1j}
#2	The average amount of security/ protection dollars per year over the life cycle of the project	Security	x_{2j}
#3	The average amount of operations and maintenance dollars per year over the life cycle of the project	O&M	x_{3j}
Output			
#1	Weighted average of the number of people served by infrastructure project per month over the lifecycle of the infrastructure component	Average number of people served	y_{1j}
#2	Weighted average of the number of people employed over the lifecycle of the infrastructure component	Average number of people employed	y_{2j}
#3	Weighted average of the number of displaced civilians that will be prevented over the lifecycle of the infrastructure component	Average number of displacements prevented	y_{3j}
#4	Weighted average of the number of people that will have access to a modern, secular secondary education over the lifecycle of the infrastructure component	Average number of people with access to education	y_{4j}

Figure 30. Summary of the Critical Infrastructure Portfolio Selection Model Inputs and Outputs.

e. The set of all critical infrastructure failure modes, t_{dj}.

i. The set of all failure modes, indexed by failure mode, d, and project, j.

ii. There are $d = 1 \ldots D$ possible failure modes for a single piece of infrastructure.

iii. The cardinality of t_{dj} is $|D| \text{ x } |n_p|$.

iv. An example of the first failure mode, d, of the first project, j.

t_{11} = {bomb}.

v. There is a relationship between a failure mode and the amount of resources (inputs) allocated to prevent it. Specifically, "protection dollars" (input #2) can be used to "buy down" probability of failure due to a bomb attack. Whereas, "operations and maintenance (O&M) dollars" (input #3) can be used to buy down probability of failure due to negligence or the improper operation and maintenance of a particular infrastructure component.

vi. See description of the probability of failure, p_{dj}, below.

2. Parameters (Data):

   a. The amount of input (resource) i required for project j (x_{ij}).

      i. x_{ij} represents a scalar value which represents a given quantity (i.e. it is not a vector or array, it is just a single number).

      ii. As an example, assume that it will require $50,000 of new construction dollars (i= 1) to construct the electricity generating plant (j = 1). Therefore, x_{11} = 50.

      iii. The values for x_{ij} will be used to populate the resource interaction matrices (U^i), defined below.

b. The amount of benefit (output) *r* expected from project *j* for given success (y_{rj}).

   i. y_{rj} represents a scalar value which represents a given quantity (i.e. it is not a vector or array, it is just a single number).

   ii. As an example, assume that if I choose to undertake the electricity generating plant construction project (j = 1), I will be able to serve (based on a weighted average) 20,000 people per month over the lifecycle of the infrastructure component (r = 1). Therefore, r_{11} = 20.

   iii. The values for y_{rj} will be used to populate the value interaction matrices (V^r), defined below.

c. The total amount of input (resource) *i* available (R_i).

   i. Indexed by subscript *i*.

   ii. This value will serve as a constraint (upper bound) on the number of projects *j* that can be undertaken in a particular portfolio *k*.

d. The resource interaction matrix of input (resource), *i* (U^i).

   i. Indexed by superscript *i*.

ii. The diagonal of this matrix indicates how much of a particular input (or resource), *i*, is required for each of the candidate projects, *j*, within the set, *G* (see explanation above for parameter x_{ij}). However, the lower diagonal portion of the matrix indicates how much of an input can be conserved if two projects are selected for inclusion within the portfolio Q_k.

$$U^1 = \begin{bmatrix} 50 & & \\ -5 & 10 & \\ -4 & -3 & 25 \end{bmatrix}$$

iii. In the case of this example, the first input, $i = 1$, is the capital improvement/ new construction budget. Therefore, U^1 indicates both the budget requirement for each of the *j* projects (along the diagonal of the matrix), as well as the resource interactions between projects. Hence, the entry $u^1_{2,1} = -5$ indicates that should one choose to undertake both project 2 (water pumping station) and project 1 (electricity generating plant), an overall cost savings of $5000 would result due to the fact that the water pumping station would no longer require a separate generating facility (since it would obtain its electricity from the plant that was scheduled for construction).

e. The value interaction matrix of output (benefit), *r* (V^r).

   i. Indexed by superscript *r*.

ii. The diagonal of this matrix indicates the relative amount of outputs (or benefits), *r*, that are yielded for each of the candidate projects, *j*, within the set, *G*. However, the lower diagonal portion of the matrix indicates how much more of an output can be realized if two projects are selected for inclusion within the portfolio Q_k.

$$V^1 = \begin{bmatrix} 20 & & \\ 15 & 30 & \\ 50 & 30 & 50 \end{bmatrix}$$

iii. In the case of this example, the first output, r = 1, is the weighted average of the number of people served by infrastructure project per month over the lifecycle of the infrastructure component. Therefore, V^1 indicates both the average number of people that will be served by each of the *j* projects (along the diagonal of the matrix), as well as the benefit interactions between projects. Hence, the entry $v^1_{2,1}$ = 15 indicates that should one choose to undertake both project 2 (water pumping station) and project 1 (electricity generating plant), 15,000 more people would be served than if only one or the other project was undertaken.

f. The probability of failure of project, j, due to threat (failure) mode, d, (p_{dj}).

   i. Indexed by the failure mode, d, and project, j.

   ii. While there is a relationship between input amounts and probabilities of failure for an infrastructure component, the Critical Infrastructure Portfolio Selection Model does not currently have a mathematical equation defining the nature of these relationships.

3. Variables

   a. The binary variable to indicate whether project j is contained within portfolio k (z_{jk}).

      i. The value of $z_{jk} = \begin{cases} 1, & if\ j \quad contained \quad in \quad k \\ 0, & otherwise \end{cases}$

      ii. Consider the case of portfolio 2, $z_2 = \{1,0,1\}$, where the electricity generating plant (j = 1) and the children's hospital (j = 3) are being undertaken, while the water pumping station (j = 2) is not. Therefore, z_{12} and z_{32} = 1, while z_{22} = 0.

   b. The amount of input (resource) i required for portfolio k $\left(\hat{x}_{ik}\right)$ (analogous to the explanation of x_{ij}).

   c. The amount of output (benefit) r required for portfolio k $\left(\hat{y}_{rk}\right)$ (analogous to the explanation of y_{rj}).

d. The variables (or weights) associated with the DEA model, (ν, μ)

   i. The variable associated with input weights in the model, ν.

   ii. The variable associated with output weights in the model, μ.

   iii. The DEA model uses a linear program (LP) to manipulate each of these respective variables in a manner that places each project, *j*, in the most favorable light (i.e. ensures that the project maximizes "DEA efficiency"), with respect to the other projects.

   iv. Since each DEA model iteration consists of a different objective function, these weighted variables can assume different values each iteration of the model.

   v. Therefore, it is possible for multiple projects to achieve 100% DEA efficiency.

   vi. One way to restrict the value that these weighted variables can obtain is to place a lower bound (other than zero) on these weighted variables based on the perceived level of importance of a particular attribute. For example, if a commander feels that the "number of people served" (output #1) has a global weight of 0.50 (with the cumulative total of either input or output weights equal to one), then this can be established as a lower bound on μ_1 and prevent unrealistic weights from being achieved – which may distort the DEA efficiency of candidate projects, *j*.

4. Constraints: There are four different types of constraints

    a. The first set of constraints are the resource (input), i, availability constraint and is defined as:

        i. The amount of a particular resource required for the sum of possible projects, j, contained within a particular portfolio, k, cannot exceed the total amount of resources available.

        ii. Mathematically: $\hat{x}_{ik} \leq \quad R_i \qquad \forall i$

        iii. As an example, assume that the total amount of new construction budget dollars equals \$70,000 (R_1 = 70). Given that x_{11} = 50, x_{22} = 10 , and x_{33} = 25, I can undertake the following portfolios of projects (where the first placeholder value (z_{1k}) represents the electricity generating plant; the second placeholder value (z_{2k}) represents the water pumping station; and the third placeholder value (z_{3k}) represents the children's hospital): z_3 = {1,1,0}, z_4 = {0,1,1}, z_5 = {1,0,0}, z_6 = {0,1,0}, and z_7 = {0,0,1}. All other portfolios (z_1 and z_2) are infeasible given my current level of funding for new construction.

b. The second set of constraints are the non-negativity constraints on the DEA model variable weights.

   i. See the preceding discussion on the relevance of weighed variables.

   ii. Mathematically: $\nu_i, \quad \mu_r \geq 0$

c. The third set of constraints ensures that the difference between the weighted sum of outputs and the weighted sum of inputs is less than, or equal to zero.

   i. This constraint occurs as a result of linearizing the DEA model (see Figures 19 and 20), which permits the DEA model to be solved using a linear program (LP).

   ii. The number of these constraints is equal to the number of projects under consideration, n_p.

   iii. Mathematically: $\sum_i \mu_i y_{ij} - \sum_i \nu_i x_{ij} \leq 0 \quad \forall\, j$

d. The fourth, and final, set of constraints simply prevent the weighted sum of inputs from being greater than one (since no project, *j*, can transform inputs to outputs more than 100%).

   i. The number of these constraints is equal to the number of projects under consideration, n_p.

   ii. Mathematically: $\sum_i \nu_i x_{ij} = 1 \quad \forall j$

Addressing the Data Requirement of the Critical Infrastructure Portfolio Selection Model

The goal of any decision-support system (DSS) is to maximize the value of the information derived by the decision-maker, while minimizing the overhead associated with collecting, entering, and managing the data that is required for the DSS to operate. This requirement is especially critical in occupations that operate primarily in austere and time-constrained environments. Therefore, one of the critical enablers that will facilitate the full implementation of the Critical Infrastructure Portfolio Selection Model, is the data layer of the DSS.

According to the Access 2003 Bible, the steps associated with developing an effective data layer (or database) for a DSS include:

Step 1: Overall System Design (What must the system do?)

Step 2: Report (Output) Design

Step 3: Data (Fields) Design

Step 4: Table (Relationships) Design

Step 5: Field (Validation) Design

Step 6: Form (Input) Design

Step 7: Menu (Automation) Design

However, given that a more detailed overview of the data layer will be provided in Appendix A of this thesis, this chapter will only outline the first step of the database design process, overall system design. The list of functionality includes:

a. Permit data entry for infrastructure projects
b. Maintain input (budget) requirements for projects
c. Maintain expected output contributions for projects

d. Maintain threat info/ failure modes for projects
e. Maintain dependency info for projects – this dependency info must relate a given project to outputs from other projects
f. Maintain probability of failure modes for projects

Summary of Research Methodology

The chapter started with a restatement of the need for a tool like the Critical Infrastructure Portfolio Selection Model. It continued with a fairly detailed explanation of several of the major system requirements that must be accounted for in order to permit the Critical Infrastructure Portfolio Selection Model to satisfy user needs. The discussion of major requirements included explanations of system life cycle considerations, identification of input-output measurements and metrics, and the notion of project success in the face of various failure modes. The remainder of the chapter was then dedicated to a complete description of the mathematical structure underlying the Critical Infrastructure Portfolio Selection Model, as well as a brief overview of a proposed database layer of the model. Therefore, given an explanation of the theoretical underpinnings of the Critical Infrastructure Portfolio Selection Model, it is now necessary to conduct an analysis which demonstrates the efficacy of such a tool.

CHAPTER 4

ANALYSIS

Overview of Methodology and Parameters

The purpose of this chapter is to demonstrate a practical application of the methodology presented in chapter 3. Towards that end, it is both useful and necessary to re-state the purpose of the Critical Infrastructure Portfolio Selection Model, which, ultimately, is to develop a methodology to help policy makers prioritize the allocation of limited resources while working towards the achievement of short and long term security objectives via the construction, security, and maintenance of critical infrastructure within a stability operations environment.

Figure 31 seeks to provide a graphical depiction of a general assumption about the traditional stability operations lines of effort (LOEs) which serve as major part of the design philosophy behind the Critical Infrastructure Portfolio Selection Model's raison d'être. Namely, that non-indigenous actors, such as coalition military forces, must take the lead in satisfying the most fundamental "Maslow" needs, such as physical security and essential services, of an affected population within a stability operations environment, during the "golden hour" of opportunity, before the host nation can provide effective, indigenous governance and security. Furthermore, a related assumption is that the only way a country engaged in stability operations will ever achieve true long-term "stability" is via its ability to attract and retain foreign capital outside of its primary commodity export sector (e.g. oil, diamonds, timber) (Collier and Hoeffler, 2001, 16). However, Thomas Friedman, in his bestseller, *The World is Flat*, states repeatedly that before this long-term stability through economic integration with the modern world can

be achieved, the HN must be able to govern itself effectively and maintain a monopoly on the use of force within its own borders. Hence, the sequential and hierarchical nature of the LOE diagram. Of course, this is not to suggest that the LOEs should not be pursued simultaneously, simply that the relative effectiveness of each successively higher tier of the "LOE hierarchy" (Figure 31) is dependent upon the lower tier which precedes it. Thus, an inherently unstable country can only achieve long-term stability once it achieves a higher state of economic development and interdependence with other national economies, yet none of this can occur until decision-makers account for the construction, protection, and proper maintenance of critical infrastructure.

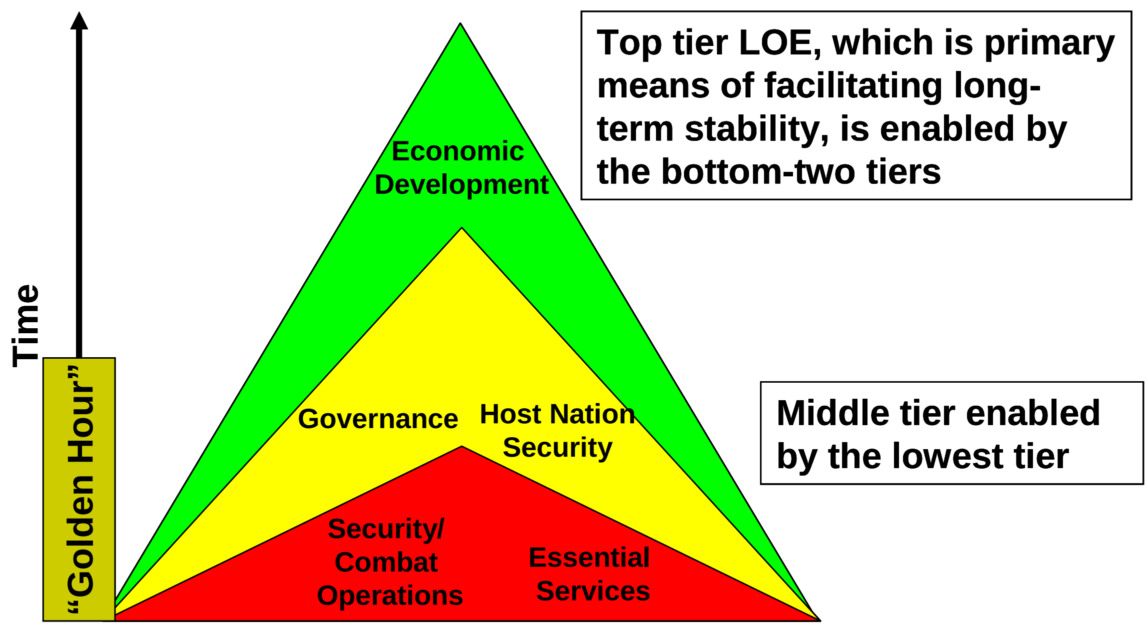


Figure 31. Success in a Counterinsurgency (COIN) and/ or Stability Operations Environment Rests Upon the Foundation of Being able to Secure and Provide Essential Services to the Affected Population.

The Critical Infrastructure Portfolio Selection Model provides a quantitative means of ensuring that critical infrastructure projects, and portfolios of projects, are prioritized based on their ability to render essential services to a population within a stability operations environment. The Critical Infrastructure Portfolio Selection Model enables decision-makers to do this by considering the entire population of relevant critical infrastructure components, which are then represented within the model by the set of possible projects (n_p). The model then considers individual project inputs (x_{ij}), outputs (y_{rj}), and probabilities of success; as well as the interaction effects that occur between projects, in order to generate sets of "efficient," or Pareto optimal, portfolios of projects which best satisfy customer needs $\left(\hat{y}_{rk}\right)$ via the most effective allocation of scarce resources $\left(\hat{x}_{ik}\right)$, subject to known resource constraints. It should also be noted, as was stated previously, that the analytical foundation for the Critical Infrastructure Portfolio Selection Model has been taken largely from three primary schools of thought. The DEA-based methodology and discussion of optimal portfolio generation techniques comes from Eilat, et al. Similarly, Lewis and his discussion of interdependencies among infrastructure components lay the foundation for determining the aggregate output benefits associated with individual projects, along with determining project success. While the Critical Infrastructure Portfolio Selection Model utilizes the methods of criteria weighting and factor analysis, to include sensitivity analysis, proposed by Parnell, et al.

Figure 32 provides a graphical orientation of an urban area in Iraq. The twenty five ovals in the figure represent the twenty five separate critical infrastructure projects that were considered during the course of this analysis. Regarding the raw data set used throughout this analysis, the majority of the data for this analysis came from USACE's

Engineer Infrastructure and Intelligence Reachback Center (EI2RC) website, a Japanese consulting firm's 2006 feasibility study of a provincial water ministry in Iraq, and open-sources available within the public domain (i.e. the internet and engineering references). However, in a few instances, especially with respect to determining protection costs (i.e. Input #2, x_{2j}) and the average number of people served by an infrastructure project per month (i.e. Output #1, y_{1j}), it was necessary to estimate values based off of information extrapolated from other known, or estimated, sources of data. Descriptions of each of the twenty five critical infrastructure component projects are shown in Figures 33 and 34.

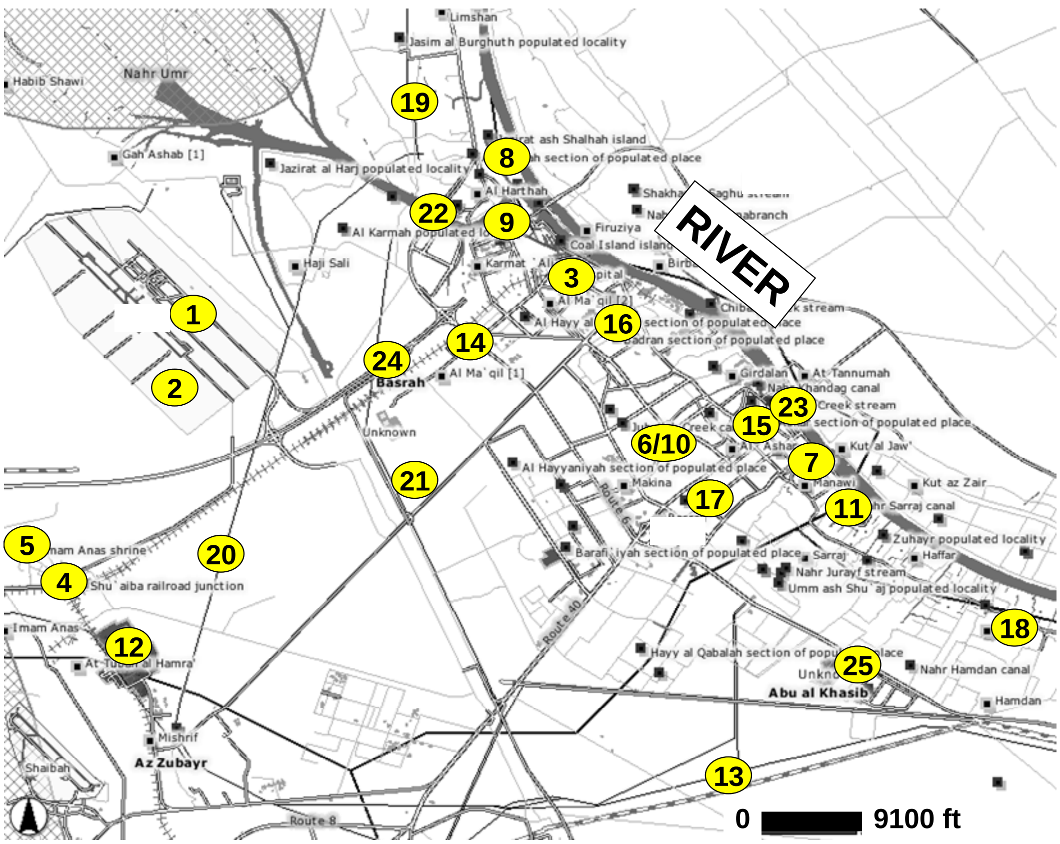


Figure 32.   Physical Locations of the Twenty Five Critical Infrastructure Components Under Consideration.

Figures 33 and 34 provide the individual project descriptions and the anticipated design lives of each of the projects. This baseline information is crucial for decision-makers to understand, given that each of the output MOEs refer to an average quantity of some sort (e.g. average cost per month over the design life of the project).

	Infrastructure Project	**Design life (yrs)**	**Primary Effects and Benefits**
1	Airport: Runway *(rehab)*	20	Runway that is capable of servicing large commercial and military aircraft for extended periods of time without requiring extensive repairs after each use
2	Airport: Utility building (electricity), co-generation, and rehab distribution system *(construct)*	20	Improve reliability of utilities (electricity) at airport
3	Hospital *(rehab)*	60	Modernized emergency room, operating room, and specialty clinics
4	Railroad junction/ segment of rail *(rehab)*	40	Modernize rail network -- facilitate ease of transport of goods
5	Shrine (rehab)	50	Religious/ community services
6	Rehabilitation of water distribution network	20	Reduce leakage, fix breaks, improve water pressure, and reduce non-revenue water (NRW) through effective metering/ billing
7	Rehabilitation of WTP	20	Maintain potable water production capacity and improve quality (esp. turbidity and color)
8	Construction of Transmission System	40	Enable bulk (water) distribution management and provide stable water input for distribution system via ring main, reservoir, and pumping facility
9	Construction of Water Treatment Plant	30	Increase potable water production capacity
10	Construction of Distribution System/ Facilities	40	Series of transfer pumps, elevated tanks, pipes, etc. in order to enable higher, and more stable, distribution management
11	Construction of Reverse Osmosis (RO) Plant	30	Maintain potable water production capacity and improve quality (esp. total dissolved solids (TDS))
12	Oil storage facility (rehab)	25	Modernized warehouse, material handling equipment, loading/ unloading docks, storage and transfer systems
13	Oil pipeline section (rehab)	25	Increase reliability of flow through structural improvements and improved monitoring and control systems
14	Road intersection/ interchange A (rehab)	20	Reduce congestion/ improve level of service (LOS) and throughput
15	Road intersection/ interchange B (rehab)	20	Reduce congestion/ improve level of service (LOS) and throughput

Figure 33. Description of the First Fifteen Critical Infrastructure Components Under Consideration.

	Infrastructure Project	Design life (yrs)	Primary Effects and Benefits
16	Bank (estab. Modern transaction features)	40	Banking services more readily available (ATM) and interfaced with remainder of bank/ financial infrastructure via modernized IT/ IS
17	Rehab of Sewage and industrial waste collection/ transmission system	25	Clean/ build/ repair network of collectors and interceptors to reduce levels of filth and disease
18	Wastewater treatment plant (construct)	25	Dispose of domestic and industrial wastewater in an environmentally sensitive manner
19	Electrical power distribution line segment A (rehab)	20	Reliable distributtion of electricity to customers
20	Electrical power distribution line segment B (rehab)	20	Reliable distributtion of electricity to customers
21	Electrical power distribution line segment C (rehab)	20	Reliable distributtion of electricity to customers
22	Road (surfaced) segment/ vehicle bridge A (rehab)	60	Significant repair of bridge wearing surface, superstructure, substructure to improve LOS/ throughput
23	Road (surfaced) segment/ vehicle bridge B (rehab)	60	Significant repair of bridge wearing surface, superstructure, substructure to improve LOS/ throughput
24	Road (surfaced) segment/ vehicle bridge C (rehab)	20	Repair road to improve LOS/ throughput
25	Communications tower (construct)	40	Improved cellular and wireless communications

Figure 34. Description of the Final Ten Critical Infrastructure Components Under Consideration.

The inclusion of the “design life” parameter ensures that each of the project MOEs that depend upon an average value of a given quantity, such as costs or number of people served, can be standardized. However, it should be noted that for the sake of simplicity of performing cost calculations, this analysis did not consider discount and inflation rates. Therefore, the average costs expressed in this thesis are simple, weighted, averages and will be explained in more detail in subsequent paragraphs.

Furthermore, before conducting the analysis, it is also imperative to reiterate the importance of the concept of interdependency amongst infrastructure sectors. As

previously stated, Dr. Ted Lewis' text, *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation*, is a well-renowned work that adheres to the standard infrastructure protection terminology that is laid out within the National Infrastructure Protection Plan (NIPP). Lewis is also particularly helpful due to the manner in which he attempts to model these infrastructure interdependencies using commonly accepted mathematical models and algorithms. While a detailed summary of Lewis' mathematical models and algorithms exceeds the scope of this thesis, the diagram depicted in Figure 35 provides a good graphical overview of Dr. Lewis' attempts to model interdependencies between the standard eleven infrastructure sectors findings. Specifically, as one goes down the chart, the more critical the infrastructure sector. This is because the higher levels of infrastructure are dependent upon the lower levels of infrastructure. As stated previously, this notion of dependencies and interdependencies amongst infrastructures forms a central theme during this analysis. Figures 36 and 37 indicate where the critical infrastructure projects considered for analysis fall within Lewis' hierarchy of infrastructure importance.

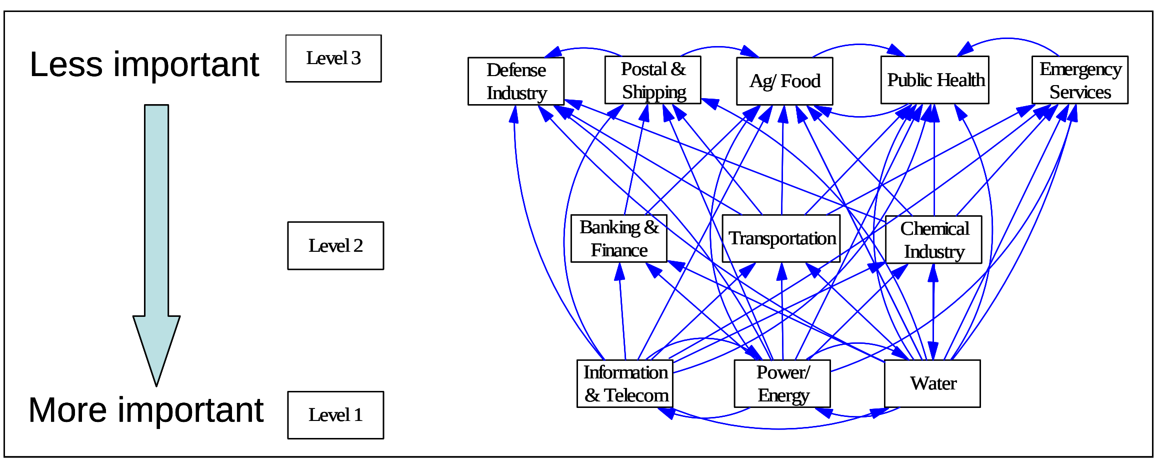


Figure 35. Author's Depiction of Dr. Lewis' Hierarchy of Critical Infrastructure Sectors.

Infrastructure Project		Infrastructure Sector(s)/ Essential Services Affected				
		Level 1		Level 2	Level 3	*Level 4*
		Water/ Wastewater	Power/ Energy	Transportation	Public Health	Cultural Icons/ Monuments
1	Airport: Runway *(rehab)*			■		
2	Airport: Utility building (electricity), co-generation, and rehab distribution system *(construct)*		■			
3	Hospital *(rehab)*				■	
4	Railroad junction/ segment of rail *(rehab)*			■		
5	Shrine (rehab)					■
6	Rehabilitation of water distribution network	■				
7	Rehabilitation of WTP	■				
8	Construction of Transmission System	■				
9	Construction of Water Treatment Plant	■				
10	Construction of Distribution System/ Facilities	■				
11	Construction of Reverse Osmosis (RO) Plant	■				
12	Oil storage facility (rehab)		■			
13	Oil pipeline section (rehab)		■			
14	Road intersection/ interchange A (rehab)			■		
15	Road intersection/ interchange B (rehab)			■		

Figure 36. Categorizing the First Fifteen Infrastructure Projects within the Standard Infrastructure Sectors.

Note: Infrastructure sectors not represented amongst the twenty five projects under consideration have been omitted from this figure.

Infrastructure Project		Infrastructure Sector(s)/ Essential Services Affected				
		Level 1			Level 2	
		Water/ Wastewater	Power/ Energy	Information/ Telecom	Banking/ Finance	Transportation
16	Bank (estab. Modern transaction features)					
17	Rehab of Sewage and industrial waste collection/ transmission system					
18	Wastewater treatment plant (construct)					
19	Electrical power distribution line segment A (rehab)					
20	Electrical power distribution line segment B (rehab)					
21	Electrical power distribution line segment C (rehab)					
22	Road (surfaced) segment/ vehicle bridge A (rehab)					
23	Road (surfaced) segment/ vehicle bridge B (rehab)					
24	Road (surfaced) segment/ vehicle bridge C (rehab)					
25	Communications tower (construct)					

Figure 37. Categorizing the Last Ten Infrastructure Projects Within the Standard Infrastructure Sectors.

Note: Infrastructure sectors not represented amongst the twenty five projects under consideration have been omitted from this figure.

As one inspects Figures 36 and 37, one will notice that, with the exception of the sectors that have been omitted due to space constraints, it conforms to the standard utilized by Dr. Lewis (in Figure 35) and the United States Government's (USG) *National Strategy for the Physical Protection of Critical Infrastructures and Key Assets*. However, the final column in Figure 36, "Cultural Icons and Monuments," while not referred to by Lewis, has also explicitly addressed within the aforementioned National Strategy document from which Lewis obtained his standard infrastructure classifications (U.S. Department of Homeland Security, 2003, 71). Further, given the relative level of importance that different cultures place on their own religious and cultural icons and monuments, it seems prudent to include this fourth level of critical infrastructure

(discussion with Parnell, et al, November 2006). Finally, it should be noted that care was taken to align projects within a single, standard infrastructure sector, even though, in some instance, some projects could arguably fit into multiple infrastructure sector categories. This convention of aligning projects within a single infrastructure category, is known as a “many-to-one” relationship, and while perhaps a bit technical, identifying relationships between data fields at this point, will greatly facilitate the ease of implementing the Critical Infrastructure Portfolio Selection Model as part of a larger suite of decision-support tools.

Obtaining Parameter Values and Determining Initial Levels of Importance

Figure 38 is indicative of the way that data was stored for use in order to arrive at the DEA model’s parameter values. The first column on the left hand side is the project description. The second column is the estimate of the “average number of people served by the infrastructure project per month *for the first six months* of the lifecycle of the infrastructure project.” Similarly, the third column is the estimate of the “average number of people served by the infrastructure project per month *from six months to the four years* of the lifecycle of the infrastructure project,” and the fourth column is the estimate of the “average number of people served by the infrastructure project per month *from four to ten years* of the lifecycle of the infrastructure project.” An entry of zero indicates that there is no direct (first-order) benefit to the people of the community during the time period indicated. The fifth column is the weighted sum of the three center columns, with the weights being ascribed as follows: 0.7 for the first column, or zero to six month period, 0.25 for the second column, or six month to four year period, and 0.05 for the third column, or four to ten year period. The purpose of weighting is to reflect the

relative importance of each of the three estimates to the overall parameter value. One of the assumptions made was that decision-makers considered it nearly three times as important to obtain early results, than to obtain them in the mid-term period, or later. In practice, it is simple to adjust these weights, but every policy-maker should take care in understanding the implications associated with doing so. Finally, it should also be noted that the three time periods reflected in Figure 38 (e.g. zero to six months) were not arbitrarily selected, but were selected based on information contained within Collier and Hoeffler's "Aid, Policy and Growth in Post-Conflict Societies" article.

		Output #1 (Avg # of People Served Per Month)			
		0 -- 6 mos	6 mos -- 4 yrs	4 -- 10 yrs	**Weighted Sum**
1	Airport: Runway (rehab)	0	100000	230000	**36500**
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	0	0	0	**0**
3	Hospital (rehab)	1000	2500	3500	**1500**
4	Railroad junction/ segment of rail (rehab)	0	0	0	**0**
5	Shrine (rehab)	5000	5000	5000	**5000**
6	Rehabilitation of water distribution network	500000	1250000	1500000	**737500**
7	Rehabilitation of WTP	500000	1250000	1500000	**737500**
8	Construction of Transmission System	0	1250000	1500000	**387500**
9	Construction of Water Treatment Plant	0	1250000	1500000	**387500**
10	Construction of Distribution System/ Facilities	0	625000	1500000	**231250**

Figure 38. Raw Data Used to Generate Output #1, y_{1j}, Values for the First Ten Projects.

The bottom line with respect to the weighting convention is that non-host nation stakeholders (e.g. coalition forces and politicians) should seek to strike a balance between a heavier emphasis on achieving meaningful outputs at the outset of a conflict or crisis, with an indigenous domestic policy that will most likely have a more long-term approach. Figure 39 shows a list of raw data for 18 of the 25 infrastructure projects. However, it should be noted that at this point, the list does not account for project dependencies, probabilities of project success, or some of the minor modifications to data (i.e. scaling) that had to occur in order to effectively implement it using the DEA-based model.

	Infrastructure Project	**Design life (yrs)**	**Input**			**Output**		
			#1	**#2**	**#3**	**#1**	**#2**	**#3**
1	Airport: Runway *(rehab)*	20	30	3.00	3.00	36500	170	0
2	Airport: Utility building (electricity), co-generation, and rehab distribution system *(construct)*	20	11	2.75	1.65	0	377	0
3	Hospital *(rehab)*	60	40	10.00	10.00	1500	1018	0
4	Railroad junction/ segment of rail *(rehab)*	40	1	0.10	0.10	0	19	0
5	Shrine (rehab)	50	0.015	0.002	0.002	5000	20	0
6	Rehabilitation of water distribution network	20	21.1	5.28	4.22	737500	913	200000
7	Rehabilitation of WTP	20	7.3	1.83	1.83	737500	166	200000
8	Construction of Transmission System	40	88.8	22.20	17.76	387500	828	60000
9	Construction of Water Treatment Plant	30	168.6	42.15	42.15	387500	333	60000
10	Construction of Distribution System/ Facilities	40	130.6	32.65	26.12	231250	1248	10000
11	Construction of Reverse Osmosis (RO) Plant	30	238.5	59.63	59.63	231250	370	10000
12	Oil storage facility (rehab)	25	100	25.00	20.00	0	155	0
13	Oil pipeline section (rehab)	25	10	2.50	1.00	0	19	0
14	Road intersection/ interchange A (rehab)	20	30	4.50	4.50	305288	353	0
15	Road intersection/ interchange B (rehab)	20	30	4.50	4.50	407050	353	0
16	Bank (estab. Modern transaction features)	40	1	0.25	0.15	305288	168	0
17	Rehab of Sewage and industrial waste collection/ transmission system	25	5.5	1.38	1.10	475000	828	200000
18	Wastewater treatment plant (construct)	25	38	9.50	9.50	387500	333	60000
	Electrical power distribution line							

Figure 39. Raw Data Associated with Each of the Possible Critical Infrastructure Components.

For the purpose of this thesis, *inputs* are measured in millions of U.S. dollars, whereas *outputs* are measured in terms of the MOEs already presented, which generally equate to the numbers of people served per month. Figure 40 offers a recap of input and output definitions.

Input	**Description**	**Short Name**	**Mathematical Symbol**
#1	The amount of capital budget/ new construction dollars *(a one time cost)*	New Construction	x_{1j}
#2	The average amount of security/ protection dollars per year over the life cycle of the project	Security	x_{2j}
#3	The average amount of operations and maintenance dollars per year over the life cycle of the project	O&M	x_{3j}
Output			
#1	Weighted average of the number of people served by infrastructure project per month over the lifecycle of the infrastructure component	Average number of people served	y_{1j}
#2	Weighted average of the number of people employed over the lifecycle of the infrastructure component	Average number of people employed	y_{2j}
#3	Weighted average of the number of displaced civilians that will be prevented over the lifecycle of the infrastructure component	Average number of displacements prevented	y_{3j}
#4**	Weighted average of the number of people that will have access to a modern, secular secondary education over the lifecycle of the infrastructure component	Average number of people with access to education	y_{4j}

Figure 40. Description of Critical Infrastructure Portfolio Selection Model Inputs and Outputs.

Before continuing, it should be noted that during the data collection period, it was observed that the values obtained for Output #4 were limited in scope, resulting in a very sparse matrix that was not significantly different from other values in the other output

categories. This development, coupled with the relatively low priority placed on this factor caused it to be removed as a criterion for project (and portfolio) evaluation. Furthermore, it will be shown during the sensitivity analysis section of this chapter that the omission of this final output category would not have had an impact on any of the final recommendations, even it were to be included in the analysis.

The next topic that will be addressed is the notion of interdependencies and dependencies that exist among critical infrastructure projects. As stated previously, several authors address this concept, to include Lewis. Rinaldi, et. al., in their article, "Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies," explain the different types of interdependencies that exist between infrastructure sectors. For the sake of brevity, an explanation of these different relationships has been omitted. What is important to understand for the sake of the Critical Infrastructure Portfolio Selection Model, is that just like there are interdependencies, and dependencies, between infrastructure sectors, there are also interdependencies, and dependencies, that exist between components within and across infrastructure sectors. However, it is important to note that since this version of the Critical Infrastructure Portfolio Selection Model was implemented using MS Excel, the model could only attempt to model one-way (dependent) relationships between projects. In other words, a project, upon which multiple projects are dependent, possesses greater benefits (outputs) since it not only yields benefits of its own to the affected population, but it also captures the benefits yielded by the dependent projects. Figure 41 depicts this explanation graphically. One should note that feedback from Project C to Project A cannot be explicitly captured via

the dependency framework as explained previously, but the nature of the relationship can be captured by the interaction matrices that will be introduced later within this chapter.

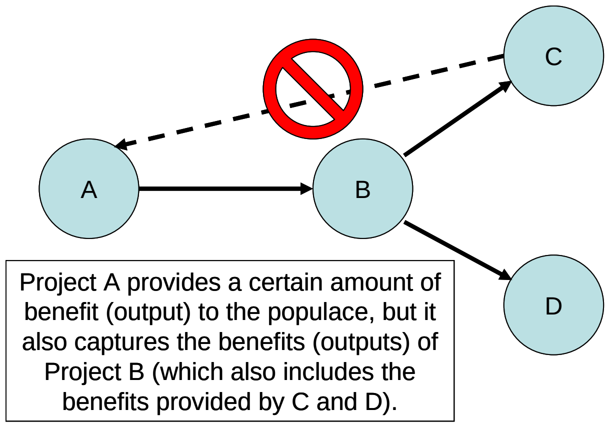


Figure 41. Graphical Depiction of the Manner in Which Project Dependencies Were Modeled in Excel.

Figure 42 depicts the entire dependency framework that is captured by the Critical Infrastructure Portfolio Selection Model, with projects listed along the vertical and horizontal axes, and shaded cells within the matrix indicating whether or not one project is dependent upon another. Figure 43 depicts a summarized, ordered, list of the results.

	Infrastructure Project	Airport: Runway (rehab)	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	Hospital (rehab)	Railroad junction/ segment of rail (rehab)	Shrine (rehab)	Rehabilitation of water distribution network	Rehabilitation of WTP	Construction of Transmission System	Construction of Water Treatment Plant	Construction of Distribution System/ Facilities	Construction of Reverse Osmosis (RO) Plant	Oil storage facility (rehab)	Oil pipeline section (rehab)	Road intersection/ interchange A (rehab)	Road intersection/ interchange B (rehab)	Bank (estab. Modern transaction features)	Rehab of Sewage and industrial waste collection/ transmission system	Wastewater treatment plant (construct)	Electrical power distribution line segment A (rehab)	Electrical power distribution line segment B (rehab)	Electrical power distribution line segment C (rehab)	Road (surfaced) segment/ vehicle bridge A (rehab)	Road (surfaced) segment/ vehicle bridge B (rehab)	Road (surfaced) segment/ vehicle bridge C (rehab)	Communications tower (construct)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Airport: Runway (rehab)	1P																								
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	1P	1P																							
3	Hospital (rehab)			1P																						
4	Railroad junction/ segment of rail (rehab)				1P								1P													
5	Shrine (rehab)					1P																				
6	Rehabilitation of water distribution network			1P		1P	1P						1P				1P		1P							1P
7	Rehabilitation of WTP						1P	1P			1P															
8	Construction of Transmission System	1P	1P					1P	1P	1P		1P							1P							
9	Construction of Water Treatment Plant						1P			1P	1P															
10	Construction of Distribution System/ Facilities			1P		1P					1P		1P				1P		1P							1P
11	Construction of Reverse Osmosis (RO) Plant						1P				1P	1P														
12	Oil storage facility (rehab)												1P													
13	Oil pipeline section (rehab)												1P	1P												
14	Road intersection/ interchange A (rehab)														1P		1P									
15	Road intersection/ interchange B (rehab)															1P	1P		1P					1P		1P
16	Bank (estab. Modern transaction features)																1P	1P								
17	Rehab of Sewage and industrial waste collection/ transmission system												1P					1P	1P							
18	Wastewater treatment plant (construct)																		1P							
19	Electrical power distribution line segment A (rehab)		1P	1P			1P	1P	1P	1P	1P	1P			1P	1P	1P	1P	1P	1P	1P	1P				1P
20	Electrical power distribution line segment B (rehab)				1P	1P							1P								1P					
21	Electrical power distribution line segment C (rehab)													1P								1P				
22	Road (surfaced) segment/ vehicle bridge A (rehab)			1P													1P						1P		1P	
23	Road (surfaced) segment/ vehicle bridge B (rehab)			1P				1P				1P					1P							1P		
24	Road (surfaced) segment/ vehicle bridge C (rehab)	1P		1P		1P											1P								1P	
25	Communications tower (construct)	1P	1P	1P				1P		1P		1P	1P				1P		1P							1P

Figure 42. Dependencies Between the Possible Critical Infrastructure Components (Projects).

#	Infrastructure Project	# of dependent components
19	*Electrical power distribution line segment A (rehab)*	17
25	*Communications tower (construct)*	10
6	*Rehabilitation of water distribution network*	7
8	*Construction of Transmission System*	7
10	*Construction of Distribution System/ Facilities*	7
23	*Road (surfaced) segment/ vehicle bridge B (rehab)*	5
24	*Road (surfaced) segment/ vehicle bridge C (rehab)*	5
15	*Road intersection/ interchange B (rehab)*	5
20	*Electrical power distribution line segment B (rehab)*	4
22	*Road (surfaced) segment/ vehicle bridge A (rehab)*	4
7	*Rehabilitation of WTP*	3
9	*Construction of Water Treatment Plant*	3
11	*Construction of Reverse Osmosis (RO) Plant*	3
17	Rehab of Sewage and industrial waste collection/ transmission system	3
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	2
4	Railroad junction/ segment of rail (rehab)	2
13	Oil pipeline section (rehab)	2
14	Road intersection/ interchange A (rehab)	2
16	Bank (estab. Modern transaction features)	2
21	Electrical power distribution line segment C (rehab)	2
1	Airport: Runway (rehab)	1
3	Hospital (rehab)	1
5	Shrine (rehab)	1
12	Oil storage facility (rehab)	1
18	Wastewater treatment plant (construct)	1

Figure 43. Ranking of Critical Infrastructure Components Based Solely on the Number of Dependent Components.

Not surprisingly, those projects that have many projects dependent upon them are typically those projects that reside in the aforementioned “Level 1” infrastructure sectors: Water, Energy, and Telecom. It is also important to note that while this thesis only accounted for dependencies among the twenty five infrastructure projects under consideration, in practice, it is paramount that dependency calculations account for as many projects as possible in order to obtain an accurate measure of the impact of the infrastructure investment. Unfortunately, due to a lack of available data of other, existing critical infrastructure components in the immediate vicinity, this approach was not

adopted within the body of this chapter. Therefore, it should be noted that any conclusions drawn from the results and analysis presented in subsequent sections of this chapter are based solely on the dependency information between the twenty five projects under consideration, and do not account for the remainder of the pre-existing infrastructure components in the same urban environment.

However, before continuing it is important to note that Figure 44 represents a “Pareto Analysis” graph of the same information that is listed in Figure 43. As you should recall from the introductory chapter of this thesis, the “Pareto principle” roughly states that eighty percent of the value come from twenty percent of the population. Hence, the twenty percent of the population which added-value to the recommended alternative or solution were generally considered to be “the vital few,” while the remaining eighty percent of the population were considered to be the “trivial many.” While this is certainly not a scientifically exact measure, this technique is used frequently by the Department of Systems Engineering at the United States Military Academy and will be applied throughout this chapter to point out its ease of use, general applicability in a time-compressed environment, and also to validate Lewis’ concept of “critical node” analysis. With this in mind, the purpose of the graph is to distinguish the “vital few” projects from amongst the “trivial many” number of possible projects. For the sake of this thesis, one should consider any item to the left of the eighty percent line as being part of the “vital few” projects, and something that decision-makers should keep their eye on as a potential investment opportunity (Parnell, et al., 2008).

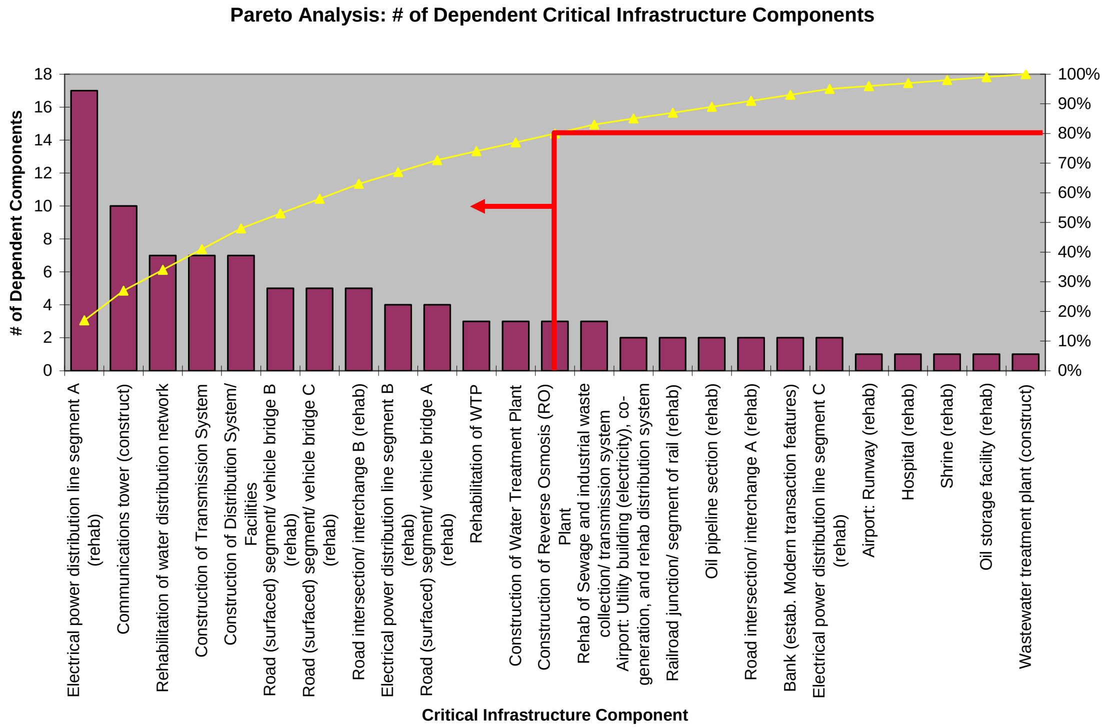


Figure 44. Graphical Depiction of the Relative Importance of the Critical Infrastructure Components Based Solely on Number of Dependent Components.

After establishing dependency relationships, it was then possible to calculate the aggregate of the number of people (from which Output #1 is derived) served by each of the infrastructure projects.

#	Infrastructure Project	Sum of Interdependencies (Output 1)
19	*Electrical power distribution line segment A (rehab)*	5,499,447
25	*Communications tower (construct)*	2,497,038
8	*Construction of Transmission System*	2,167,750
6	*Rehabilitation of water distribution network*	1,846,788
15	*Road intersection/ interchange B (rehab)*	1,706,888
7	*Rehabilitation of WTP*	1,706,250
23	*Road (surfaced) segment/ vehicle bridge B (rehab)*	1,472,588
9	Construction of Water Treatment Plant	1,356,250
10	*Construction of Distribution System/ Facilities*	1,340,538
11	Construction of Reverse Osmosis (RO) Plant	1,200,000
17	Rehab of Sewage and industrial waste collection/ transmission system	862,500
16	Bank (estab. Modern transaction features)	780,288
14	Road intersection/ interchange A (rehab)	610,575
22	Road (surfaced) segment/ vehicle bridge A (rehab)	482,560
18	Wastewater treatment plant (construct)	387,500
24	Road (surfaced) segment/ vehicle bridge C (rehab)	376,272
21	Electrical power distribution line segment C (rehab)	267,050
1	Airport: Runway (rehab)	36,500
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	36,500
20	Electrical power distribution line segment B (rehab)	32,985
5	Shrine (rehab)	5,000
3	Hospital (rehab)	1,500
4	Railroad junction/ segment of rail (rehab)	0
12	Oil storage facility (rehab)	0
13	Oil pipeline section (rehab)	0

Figure 45. Ranking of Critical Infrastructure Components Based Solely on the Cumulative Sum of the *Average Number of People Served Per Month* (Output #1).

While the projects at the top of the list of Figure 45 are very similar to those indicated in Figures 43 and 44, one can see an even greater variance between those projects considered to be the "most important" at the top of the list, and those projects considered to be the "least important" at the bottom of the list. Furthermore, after closer inspection, one should observe that three of the projects at the bottom of the list, railroad junction/ segment of rail, oil storage facility, and oil pipeline section, if not rebuilt, secured, or maintained, could have potential short- and long-term implications upon the affected population's *economic system* (which directly impacts the long-term stability of the affected community or region – see Figure 31). Therefore, how can these projects be at the bottom of the list? To understand this, it is necessary to understand that these projects are evaluated by the Critical Infrastructure Portfolio Selection Model based on their

ability to satisfy *first-order* benefits to the affected population. Therefore, if there is ultimately no first-order connection, or "hook" between the projects being considered and the populace, the benefits (outputs) of the projects cannot be aggregated and potentially important projects might be omitted. That is why it is necessary to consider all projects and dependencies in the operating environment. Unfortunately, this necessity also causes the scope of the Critical Infrastructure Portfolio Selection Model to increase quickly. Fortunately, though, the fact that this model considers portfolios of projects, instead of individual project evaluations, actually serves as a great strength in this regard, as will be demonstrated later. The important take-away from this section is that it has been demonstrated on numerous occasions in both Afghanistan and Iraq this decade, that infrastructure projects that might be important at the community level, might not have the same level of importance at the national level. Therefore, the method (and level) of aggregation is important, and must be considered by the decision-maker before adopting any recommendations made on the basis of this (or any) model. Figure 46 (below) simply provides a graphical depiction of the information that was presented in tabular format in Figure 45.

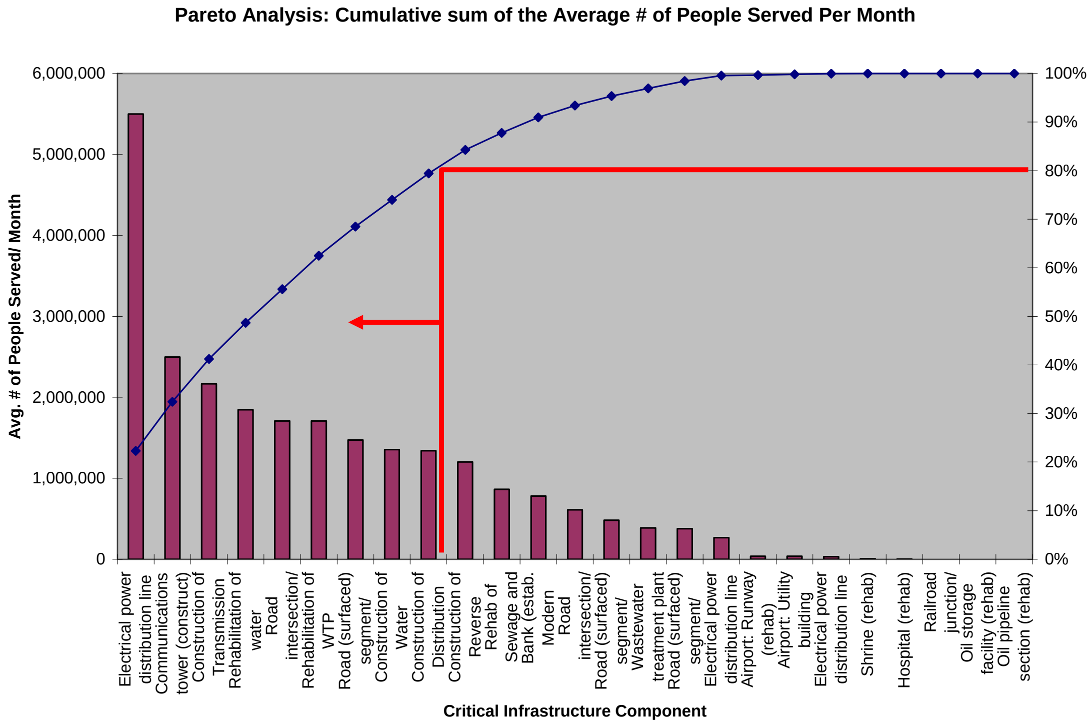


Figure 46. Graphical Depiction of the Relative Importance of the Critical Infrastructure Components Based Solely on Cumulative Sum of the *Average Number of People Served Per Month* (Output #1).

Similarly, Figures 47 and 48, on the following page, attempt to provide the same sort of summary information for each of the projects based on the second MOE, the *average number of people employed per month*. As has been mentioned previously in this thesis, the first two stated benefits, “Number of people served” and “Number of people employed” were selected and prioritized as the two most important MOEs based on interviews with several senior ranking PRT members and Iraqi provincial water ministers (Trainor, et al, 2007).

#	Infrastructure Project	# of People Employed (Output 2)
10	*Construction of Distribution System/ Facilities*	1248
3	*Hospital (rehab)*	1018
6	*Rehabilitation of water distribution network*	913
8	*Construction of Transmission System*	828
17	*Rehab of Sewage and industrial waste collection/ transmission system*	828
2	*Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)*	377
11	*Construction of Reverse Osmosis (RO) Plant*	370
14	*Road intersection/ interchange A (rehab)*	353
15	*Road intersection/ interchange B (rehab)*	353
9	*Construction of Water Treatment Plant*	333
18	Wastewater treatment plant (construct)	333
25	Communications tower (construct)	306
1	Airport: Runway (rehab)	170
16	Bank (estab. Modern transaction features)	168
7	Rehabilitation of WTP	166
12	Oil storage facility (rehab)	155
22	Road (surfaced) segment/ vehicle bridge A (rehab)	73
23	Road (surfaced) segment/ vehicle bridge B (rehab)	73
19	Electrical power distribution line segment A (rehab)	37
20	Electrical power distribution line segment B (rehab)	37
21	Electrical power distribution line segment C (rehab)	37
24	Road (surfaced) segment/ vehicle bridge C (rehab)	37
5	Shrine (rehab)	20
4	Railroad junction/ segment of rail (rehab)	19
13	Oil pipeline section (rehab)	19

Figure 47. Ranking of Projects Based on the Cumulative Sum of the *Average Number of People Employed Per Month* (Output #2).

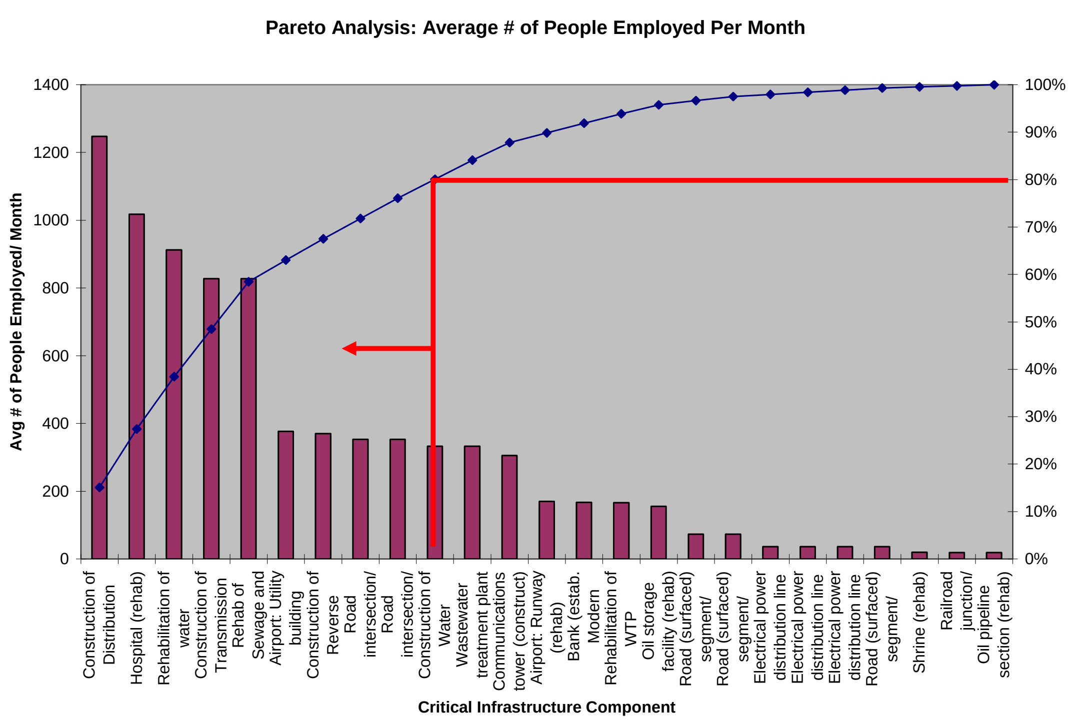


Figure 48. Relative Importance of the Critical Infrastructure Components Based on *Average Number of People Employed Per Month* (Output #2).

The next category of benefits comes, as mentioned within the literature review, from Collier and Hoeffler's "Greed and Grievance in Civil Wars," who state in their conclusion that diaspora populations actually have a tendency to prolong civil unrest and conflict. Therefore, the analysis only considered those infrastructure projects needed to sustain life based on the primary assumption that these life sustaining infrastructure components would help prevent the displacement of civilians. Projects that did not render these types of first-order benefits to the population received a raw value of zero. The raw values come from neighborhood population estimates in the area in which the proposed 25 projects are located (or soon to be located). Similarly, Figure 50 provides a Pareto Analysis graph of the data presented in Figure 49.

#	Infrastructure Project	Avg # of Displaced Civilians Prevented (Output 3)
6	*Rehabilitation of water distribution network*	200,000
7	*Rehabilitation of WTP*	200,000
17	*Rehab of Sewage and industrial waste collection/ transmission system*	200,000
19	*Electrical power distribution line segment A (rehab)*	200,000
20	*Electrical power distribution line segment B (rehab)*	200,000
21	*Electrical power distribution line segment C (rehab)*	200,000
8	Construction of Transmission System	60,000
9	Construction of Water Treatment Plant	60,000
18	Wastewater treatment plant (construct)	60,000
10	Construction of Distribution System/ Facilities	10,000
11	Construction of Reverse Osmosis (RO) Plant	10,000
1	Airport: Runway (rehab)	0
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	0
3	Hospital (rehab)	0
4	Railroad junction/ segment of rail (rehab)	0
5	Shrine (rehab)	0
12	Oil storage facility (rehab)	0
13	Oil pipeline section (rehab)	0
14	Road intersection/ interchange A (rehab)	0
15	Road intersection/ interchange B (rehab)	0
16	Bank (estab. Modern transaction features)	0
22	Road (surfaced) segment/ vehicle bridge A (rehab)	0
23	Road (surfaced) segment/ vehicle bridge B (rehab)	0
24	Road (surfaced) segment/ vehicle bridge C (rehab)	0
25	Communications tower (construct)	0

Figure 49. Ranking of Critical Infrastructure Components Based Solely on the Cumulative Sum of the *Average Number of Displaced Civilians Prevented* (Output #3).

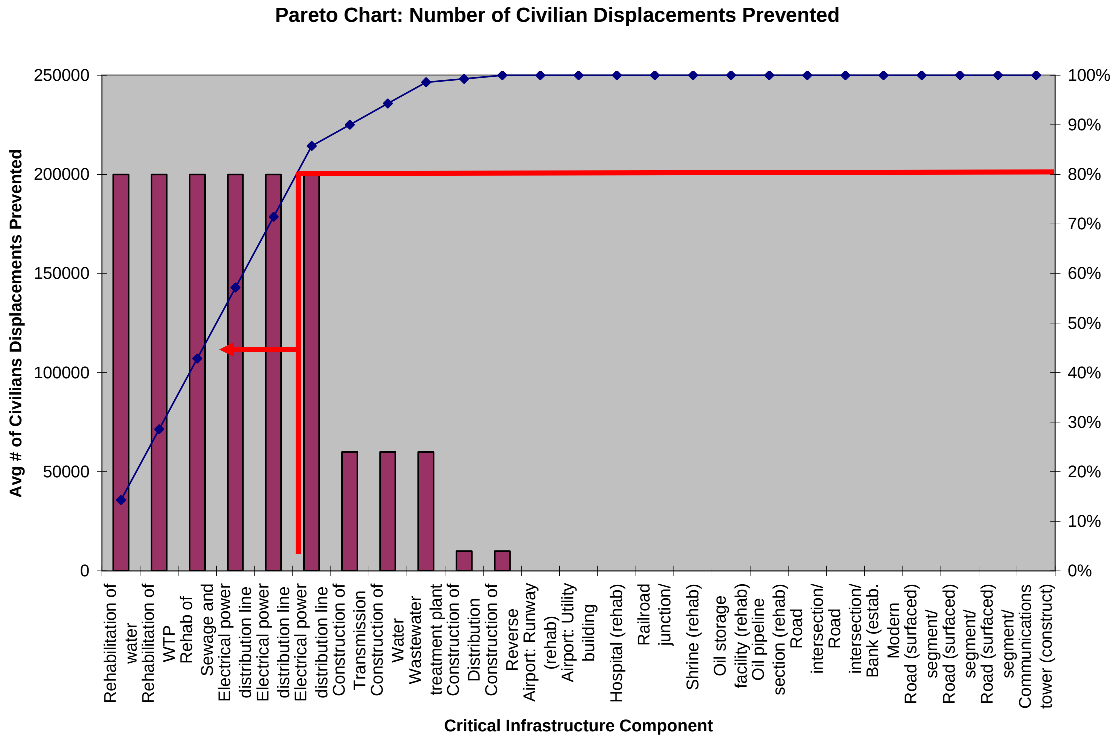


Figure 50. Graphical Depiction of the Relative Importance of Critical Infrastructure Components Based Solely on *Average Number of Civilian Displacements Prevented* (Output #3).

While Figures 51 and 52 provide a summary of the results presented in Figures 45 – 52, drawing conclusions based solely on these output-based results would be premature. The information presented thus far fails to account for project input (budget resource) requirements and constraints, individual project risk, and the manner in which individual projects transform inputs to outputs, or "project efficiency." To say nothing of the fact that project interaction effects and portfolios have yet to be considered. Therefore, before making a final policy recommendation, it is necessary to conduct a more thorough analysis using the remainder of the Critical Infrastructure Portfolio Selection Model.

Infrastructure Project		Ranking				
		# of Dependent Components	Avg. # of People Served/ Month (Output 1)	Avg. # of People Employed/ Month (Output 2)	Avg # of Civilian Displacements Prevented (Output 3)	Average Ranking (Unweighted)
6	Rehabilitation of water distribution network	3	6	3	1	3
8	Construction of Transmission System	4	3	4	7	5
10	Construction of Distribution System/ Facilities	5	7	1	10	6
19	Electrical power distribution line segment A (rehab)	1	1	19	4	6
17	Rehab of Sewage and industrial waste collection/ transmission system	14	12	5	3	9
7	Rehabilitation of WTP	11	8	15	2	9
9	Construction of Water Treatment Plant	12	9	10	8	10
11	Construction of Reverse Osmosis (RO) Plant	13	10	7	11	10
15	Road intersection/ interchange B (rehab)	8	4	9	20	10
25	Communications tower (construct)	2	2	12	25	10
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	15	16	6	13	13
20	Electrical power distribution line segment B (rehab)	9	17	20	5	13
23	Road (surfaced) segment/ vehicle bridge B (rehab)	6	5	18	23	13
3	Hospital (rehab)	22	19	2	14	14
14	Road intersection/ interchange A (rehab)	18	15	8	19	15
22	Road (surfaced) segment/ vehicle bridge A (rehab)	10	14	17	22	16
1	Airport: Runway (rehab)	21	18	13	12	16
16	Bank (estab. Modern transaction features)	19	11	14	21	16
24	Road (surfaced) segment/ vehicle bridge C (rehab)	7	13	22	24	17
18	Wastewater treatment plant (construct)	25	24	11	9	17
21	Electrical power distribution line segment C (rehab)	20	25	21	6	18
4	Railroad junction/ segment of rail (rehab)	16	20	24	15	19
12	Oil storage facility (rehab)	24	22	16	17	20
5	Shrine (rehab)	23	21	23	16	21
13	Oil pipeline section (rehab)	17	23	25	18	21

Figure 51. Summary of Critical Infrastructure Component Output (MOE) Rankings.

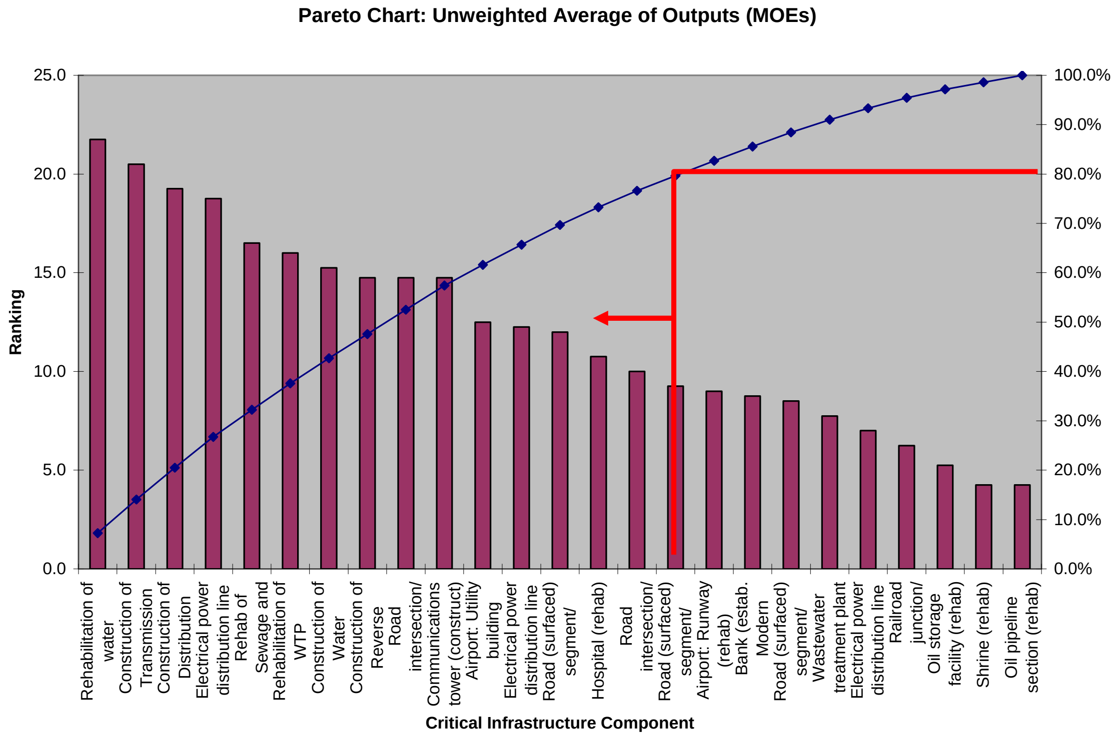


Figure 52. Graphical depiction of the relative importance of critical infrastructure components based solely on the unweighted average of output (MOE) rankings.

Individual Project Evaluation

As stated previously, data envelopment analysis (DEA) serves as the mathematical foundation of the Critical Infrastructure Portfolio Selection Model. Unlike the Pareto Analyses that ranked individual projects based on the evaluation of a single factor at a time, with no regard for resource utilization (i.e. efficiency), DEA does. Additionally, Figure 53 demonstrates the results of the individual project evaluation after the DEA model has been executed using VBA source code obtained from Ragsdale's *Spreadsheet Modeling and Decision Analysis, 4th Edition* (2004, pg. 114 – 115).

	Infrastructure Project	Input #1	Input #2	Input #3	Input Weight	Output #1	Output #2	Output #3	Output Weight	Weighted Difference	DEA Efficiency
21	Electrical power distribution line segment C (rehab)	0.005	0.010	0.01	0.01	267.05	0.0365	200	0.01	0.00	1.00
5	Shrine (rehab)	0.0003	0.002	0.0015	0.0015	5.00	0.02	0	0.0015	0.00	1.00
20	Electrical power distribution line segment B (rehab)	0.005	0.010	0.01	0.01	32.98	0.0365	200	0.01	0.00	1.00
19	Electrical power distribution line segment A (rehab)	0.005	0.010	0.01	0.01	5499.45	0.0365	200	0.01	0.00	1.00
25	Communications tower (construct)	0.025	0.250	0.2	0.2	2497.04	0.3055	0	0.0229	-0.18	0.26
16	Bank (estab. Modern transaction features)	0.025	0.250	0.15	0.15	780.29	0.1675	0	0.0126	-0.14	0.12
17	Rehab of Sewage and industrial waste collection/ transmission system	0.220	1.375	1.1	1.1	862.50	0.8275	200	0.0693	-1.03	0.08
24	Road (surfaced) segment/ vehicle bridge C (rehab)	0.025	0.050	0.05	0.05	376.27	0.0365	0	0.0027	-0.05	0.06
23	Road (surfaced) segment/ vehicle bridge B (rehab)	0.053	0.800	0.48	0.48	1472.59	0.073	0	0.0055	-0.47	0.04
22	Road (surfaced) segment/ vehicle bridge A (rehab)	0.053	0.800	0.48	0.48	482.56	0.073	0	0.0055	-0.47	0.03
3	Hospital (rehab)	0.667	10.000	10	10	1.50	1.0176	0	0.0763	-9.92	0.02
7	Rehabilitation of WTP	0.365	1.825	1.825	1.825	1706.25	0.1663	200	0.0197	-1.81	0.02
6	Rehabilitation of water distribution network	1.055	5.275	4.22	4.22	1846.79	0.9125	200	0.0757	-4.14	0.02
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	0.550	2.750	1.65	1.65	36.50	0.3765	0	0.0282	-1.62	0.02
4	Railroad junction/ segment of rail (rehab)	0.025	0.100	0.1	0.1	0.00	0.019	0	0.0014	-0.10	0.01
15	Road intersection/ interchange B (rehab)	1.500	4.500	4.5	4.5	1706.89	0.353	0	0.0265	-4.47	0.01
8	Construction of Transmission System	2.220	22.200	17.76	17.76	2167.75	0.8275	60	0.0642	-17.70	0.01
14	Road intersection/ interchange A (rehab)	1.500	4.500	4.5	4.5	610.58	0.353	0	0.0265	-4.47	0.01
10	Construction of Distribution System/ Facilities	3.265	32.650	26.12	26.12	1340.54	1.2475	10	0.0939	-26.03	0.01
1	Airport: Runway (rehab)	1.500	3.000	3	3	36.50	0.17	0	0.0128	-2.99	0.00
18	Wastewater treatment plant (construct)	1.520	9.500	9.5	9.5	387.50	0.3325	60	0.0271	-9.47	0.00
13	Oil pipeline section (rehab)	0.400	2.500	1	1	0.00	0.019	0	0.0014	-1.00	0.00
9	Construction of Water Treatment Plant	5.620	42.150	42.15	42.15	1356.25	0.3325	60	0.0271	-42.12	0.00
11	Construction of Reverse Osmosis (RO) Plant	7.950	59.625	59.625	59.625	1200.00	0.37	10	0.0281	-59.60	0.00
12	Oil storage facility (rehab)	4.000	25.000	20	20	0.00	0.155	0	0.0116	-19.99	0.00

Figure 53. DEA Model Parameters and Results Without User-Imposed Lower Bounds on Weights.

Upon further inspection of Figure 53, though, it is clear that there are some faults with the DEA model that was executed without user-imposed lower bounds. One way to overcome the most significant fault, was to impose bounds upon the DEA model weights. The purpose of imposing these lower bounds was to ensure that sufficient levels of importance were given to the various input and output measures. While imposing bounds on weights, which are the decision variables in the DEA model, is not a standard practice when implementing a DEA model, J. S. H. Kornbluth and others have successfully demonstrated occasions when imposing weight restrictions makes sense (Kornbluth,

December 1991, 1097-1104). With this in mind, Figure 54 shows the following input and output weights that were initially imposed.

Input	Weight (Lower Bound)	Short Name	Mathematical Symbol
#1	0.6	New Construction	x_{1j}
#2	0.1	Security	x_{2j}
#3	0.3	O&M	x_{3j}
Output			
#1	0.6	Average number of people served	y_{1j}
#2	0.2	Average number of people employed	y_{2j}
#3	0.2	Average number of displacements prevented	y_{3j}

Figure 54. Initial Weighting Mechanism for DEA Model.

Figure 55 displays the results of the DEA model once weights are applied. At first glance, it appears that these results appear to be much more "reasonable" in that the results appear to more closely approximate the results given in the preceding section. Unfortunately, once the bounds were imposed, Excel's solver optimization routine permitted DEA efficiencies to exceed 1.00, which, in reality, is not possible. However, this lapse was permissible for the time being, and it did illustrate the point as to why most professional analysts dislike using Excel for this type of work.

	Infrastructure Project	Input #1	Input #2	Input #3	Input Weight	Output #1	Output #2	Output #3	Output Weight	Weighted Difference	DEA Efficiency
19	Electrical power distribution line segment A (rehab)	0.005	0.010	0.01	0.187	5499.45	0.0365	200	3319.7	3319.49	3319.68
25	Communications tower (construct)	0.025	0.250	0.2	1	2497.04	0.3055	0	1498.3	1497.28	1498.28
8	Construction of Transmission System	2.220	22.200	17.76	88.8	2167.75	0.8275	60	1306.8	1218.02	1306.82
6	Rehabilitation of water distribution network	1.055	5.275	4.22	40.4065	1846.79	0.9125	200	1128.3	1087.85	1128.26
7	Rehabilitation of WTP	0.365	1.825	1.825	14.089	1706.25	0.1663	200	1043.8	1029.69	1043.78
15	Road intersection/ interchange B (rehab)	1.500	4.500	4.5	56.7	1706.89	0.353	0	1024.2	967.50	1024.20
23	Road (surfaced) segment/ vehicle bridge B (rehab)	0.053	0.800	0.48	2.176	1472.59	0.073	0	883.57	881.39	883.57
9	Construction of Water Treatment Plant	5.620	42.150	42.15	222.552	1356.25	0.3325	60	819.82	597.26	819.82
10	Construction of Distribution System/ Facilities	3.265	32.650	26.12	130.6	1340.54	1.2475	10	805.57	674.97	805.57
11	Construction of Reverse Osmosis (RO) Plant	7.950	59.625	59.625	314.82	1200.00	0.37	10	721.07	406.25	721.07
17	Rehab of Sewage and industrial waste collection/ transmission system	0.220	1.375	1.1	8.5195	862.50	0.8275	200	537.67	529.15	537.67
16	Bank (estab. Modern transaction features)	0.025	0.250	0.15	0.985	780.29	0.1675	0	468.21	467.22	468.21
14	Road intersection/ interchange A (rehab)	1.500	4.500	4.5	56.7	610.58	0.353	0	366.42	309.72	366.42
22	Road (surfaced) segment/ vehicle bridge A (rehab)	0.053	0.800	0.48	2.176	482.56	0.073	0	289.55	287.37	289.55
18	Wastewater treatment plant (construct)	1.520	9.500	9.5	59.432	387.50	0.3325	60	238.57	179.13	238.57
24	Road (surfaced) segment/ vehicle bridge C (rehab)	0.025	0.050	0.05	0.935	376.27	0.0365	0	225.77	224.84	225.77
21	Electrical power distribution line segment C (rehab)	0.005	0.010	0.01	0.187	267.05	0.0365	200	180.24	180.05	180.24
20	Electrical power distribution line segment B (rehab)	0.005	0.010	0.01	0.187	32.98	0.0365	200	39.798	39.61	39.80
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	0.550	2.750	1.65	20.9	36.50	0.3765	0	21.975	1.08	21.98
1	Airport: Runway (rehab)	1.500	3.000	3	56.1	36.50	0.17	0	21.934	-34.17	21.93
5	Shrine (rehab)	0.0003	0.002	0.0015	0.01158	5.00	0.02	0	3.004	2.99	3.00
3	Hospital (rehab)	0.667	10.000	10	28.4	1.50	1.0176	0	1.1035	-27.30	1.10
12	Oil storage facility (rehab)	4.000	25.000	20	154.9	0.00	0.155	0	0.031	-154.87	0.03
4	Railroad junction/ segment of rail (rehab)	0.025	0.100	0.1	0.955	0.00	0.019	0	0.0038	-0.95	0.00
13	Oil pipeline section (rehab)	0.400	2.500	1	15.19	0.00	0.019	0	0.0038	-15.19	0.00

	Input #1	Input #2	Input #3	Output #1	Output #2	Output #3
Weights (Calculated)	36.6	0.1	0.3	0.6	0	0.1
Weights (Lower Bound)	0.6	0.1	0.3	0.6	0.2	0.1

Figure 55. DEA Model Parameters and Results With User-Imposed Lower Bounds on Weights.

Figure 56 illustrates the stark differences that exist when running the DEA model with and without bounds. Shaded cells indicate those projects with an absolute difference of less than six between the two methods. The analysis included this comparison in order to demonstrate the impractical results that may occur if one fails to impose some sort of user-defined bound on the weights. It should be noted that a compromise, less constraining, weighting approach was used for the final analysis, which simply ensured that the most important measure weight for the inputs, Input #1, and the most important weight for the outputs, Output #1, must be greater than the remaining weights within their respective input and output categories, and this appeared to work well.

	Infrastructure Project	Ranking (w/out user imposed bounds)	Ranking (w/ user imposed bounds)	Difference between rankings
21	Electrical power distribution line segment C (rehab)	1	17	16
5	Shrine (rehab)	2	21	19
20	Electrical power distribution line segment B (rehab)	3	18	15
19	Electrical power distribution line segment A (rehab)	4	1	3
25	Communications tower (construct)	5	2	3
16	Bank (estab. Modern transaction features)	6	12	6
17	Rehab of Sewage and industrial waste collection/ transmission system	7	11	4
24	Road (surfaced) segment/ vehicle bridge C (rehab)	8	16	8
23	Road (surfaced) segment/ vehicle bridge B (rehab)	9	7	2
22	Road (surfaced) segment/ vehicle bridge A (rehab)	10	14	4
3	Hospital (rehab)	11	22	11
7	Rehabilitation of WTP	12	5	7
6	Rehabilitation of water distribution network	13	4	9
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	14	19	5
4	Railroad junction/ segment of rail (rehab)	15	24	9
15	Road intersection/ interchange B (rehab)	16	6	10
8	Construction of Transmission System	17	3	14
14	Road intersection/ interchange A (rehab)	18	13	5
10	Construction of Distribution System/ Facilities	19	9	10
1	Airport: Runway (rehab)	20	20	0
18	Wastewater treatment plant (construct)	21	15	6
13	Oil pipeline section (rehab)	22	25	3
9	Construction of Water Treatment Plant	23	8	15
11	Construction of Reverse Osmosis (RO) Plant	24	10	14
12	Oil storage facility (rehab)	25	23	2

Figure 56. Comparison of Project Rankings Based on DEA Weighting Techniques.

Project Probability of Success

The technique used for determining project vulnerability, which is the complement of project success, is based on Dr. Lewis' *Critical Infrastructure Protection in Homeland Security* text. However, before addressing the complementary notions of project success and project vulnerability, it must be noted that the primary motivation for calculating vulnerability is to be able to help decision-makers clearly articulate risks associated with any recommended portfolio of critical infrastructure projects. Lewis defines risk as the product of project vulnerability times the consequence of the action.

As an example, assume that there are three broad modes of project failure: Terrorist attack, regardless of the form that the attack takes, Operation and maintenance (O&M) failure (due primarily to an infrastructure component being operated beyond its design capacity/ limit), and dependent component failure, that is, a component upon which an infrastructure project depends, fails for some reason. Furthermore, assume that an infrastructure component will fail in accordance with the "OR" model described earlier in Chapter 3. That is to say, an infrastructure component project, *j*, will fail if any of the three aforementioned events transpire. Mathematically, this project vulnerability is expressed as the product of the probabilities of the various failure modes occurring, which is simply: $p_{terrorist\_attack} \times p_{O\&M} \times p_{dependent\_infrastructure}$. Therefore, the probability of project success is:

$$1 - (p_{terrorist\_attack} \times p_{O\&M} \times p_{dependent\_infrastructure}) = \text{Probability of project } j \text{ success}$$

Using the more concise Chapter 3 terminology, p_{dj} is the probability of project *j* failure due to factor *d*.

With this in mind, a major assumption that is needed to facilitate this portion of the analysis will be that budget requirements for protection (Input #2) and O&M (Input #3) are such that each of these first two probabilities of occurrence will only be ten percent. Put another way, the assumption is that planners have allocated enough money to the project in the protection category to ensure that there is only a ten percent chance that the project will fail due to a terrorist attack. The same holds for the O&M category. Furthermore, referring back to the instance of a protection failure, this translates to a ninety percent probability of project success (since 1 – vulnerability = probability of project success), if one is only concerned about failure due to a terrorist attack of some

sort. Furthermore, if one looks for ninety percent along the y-axis of Figure 57, one will see that the function intersects with 1.00 along the x-axis. This simply means that as long as planners spend 100% (which equates to 1.0 on the x-axis) of what is "reasonably prudent" on protecting the infrastructure project (see the "Input 2" column in either Figure 54 or 55), then the infrastructure project has a ninety percent chance of not having its levels of service (as measured by the MOEs) interrupted throughout its design life as a result of a terrorist attack. Similarly, as long as decision makers spend 100% (or 1.0) of what is already earmarked in the annual budget for project *operations and maintenance* (O&M) (see the "Input 3" column in either Figure 54 or 55), then the infrastructure project has a ninety percent chance of not having its levels of service, as measured by the MOEs, interrupted throughout its design life as a result of poor routine maintenance, or improper operator/ operating techniques or procedures. However, given that it only takes one of these two possible failure modes to cause a disruption of service, the probability of project success becomes 0.9 x 0.9 = 0.81.

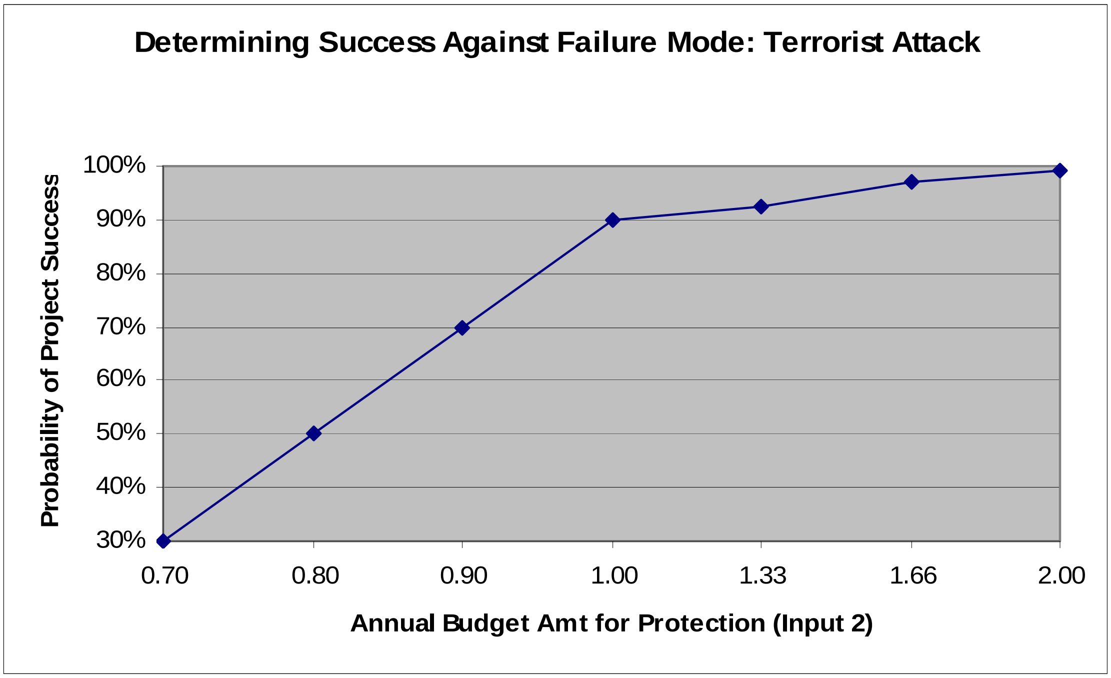


Figure 57. Probability of Project Success (Y-axis) as a Function of the Annual Protection Budget (Input #2) (X-Axis).

Note: A similar function defines the relationship between project success and the annual O&M budget.

While ninety percent probably seemed like a reasonable probability of success, and eighty one percent, while not impressive, is still most likely within the acceptable range for most infrastructure components, the preceding calculations fail to account for the event that another infrastructure project, upon which the current infrastructure project is dependent, should fail for some reason. For instance, how should one account for the probability of success of a water treatment plant that is dependent upon an external electricity source? The first probability value of interest would be the eighty one percent calculated previously. However, given that it is necessary to also account for the source of electricity, the new probability of success for the water treatment plant becomes:

0.81 *(probability of water treatment plant not failing due to protection or O&M failure)* x 0.81 *(probability of electrical distribution system success, assuming that it is not dependent upon any other infrastructure component)* = .6561 or 65%

Based on these simple calculations, the need to account for project success becomes readily apparent. However, before continuing, it is necessary to make three additional points. The first point is that Lewis makes the assumption that one is able to “buy down” vulnerability (i.e. the opposite of project success) by simply investing more in the protection budget, or the O&M budget in accordance with a constructed function or graph that might look something like Figure 57. The second point is that while threats to critical infrastructure associated with terrorist or explosive attacks tend to grab headlines, anecdotal evidence suggests that component failures due to poor host nation (HN) operation and maintenance are far more common. It goes without saying that many senior leaders and military officers involved with stability operations have come to the realization that HN ability/ willingness to operate effectively and maintain critical infrastructure components must be accounted for when deciding what types of projects to allocate resources towards, thereby reinforcing the system lifecycle considerations that have been addressed in this thesis. The third point is that it should be noted that the function introduced in Figure 57, and the examples presented in this section, have been constructed based on a completely fabricated data set for the purpose of demonstrating the efficacy of this technique. However, there is a robust set of literature dedicated to estimating probabilities of uncertain events, see Kirkwood’s *Strategic Decision Making*, or Clemen or Reilly’s *Making Hard Decisions*, and any textbook on statistics can assist the reader, as long as a data set is available, in generating a relationship (function)

between the probability of project success and the amount of money that is allocated to the various budget categories outlined in this thesis. Figure 58 (below) outlines the various project vulnerabilities used in this analysis, as computed within MS Excel.

	Infrastructure Project	Prob of Success (Protection)	Prob of Success (O&M)	Prob. Of Success (non-dependencies)	Airport: Runway (rehab)	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	Hospital (rehab)	Railroad junction/ segment of rail (rehab)	Shrine (rehab)	Rehabilitation of water distribution network	Rehabilitation of WTP	Construction of Transmission System	Construction of Water Treatment Plant	Construction of Distribution System/ Facilities	Construction of Reverse Osmosis (RO) Plant	Oil storage facility (rehab)	Oil pipeline section (rehab)	Road intersection/ interchange A (rehab)	Road intersection/ interchange B (rehab)	Bank (estab. Modern transaction features)	Rehab of Sewage and industrial waste collection/ transmission system	Wastewater treatment plant (construct)	Electrical power distribution line segment A (rehab)	Electrical power distribution line segment B (rehab)	Electrical power distribution line segment C (rehab)	Road (surfaced) segment/ vehicle bridge A (rehab)	Road (surfaced) segment/ vehicle bridge B (rehab)	Road (surfaced) segment/ vehicle bridge C (rehab)	Communications tower (construct)	Overall Prob. Of Success
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
1	Airport: Runway (rehab)	0.9	0.9	0.81		0.81																								66%
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	0.9	0.9	0.81						0.81		0.81		1							0.81		0.81						0.81	28%
3	Hospital (rehab)	0.9	0.9	0.81						0.81				1							0.81		0.81						0.81	35%
4	Railroad junction/ segment of rail (rehab)	0.9	0.9	0.81																				0.81						66%
5	Shrine (rehab)	0.9	0.9	0.81						0.81				1							0.81			0.81						43%
6	Rehabilitation of water distribution network	0.9	0.9	0.81							0.81		1		1								0.81							53%
7	Rehabilitation of WTP	0.9	0.9	0.81								0.81									0.81		0.81						0.81	35%
8	Construction of Transmission System	0.9	0.9	0.81																			0.81							66%
9	Construction of Water Treatment Plant	0.9	0.9	0.81								0.81									0.81		0.81						0.81	35%
10	Construction of Distribution System/ Facilities	0.9	0.9	0.81							0.81		1		1								0.81							53%
11	Construction of Reverse Osmosis (RO) Plant	0.9	0.9	0.81								0.81									0.81		0.81						0.81	35%
12	Oil storage facility (rehab)	0.9	0.9	0.81				0.81		0.81				1			0.81				0.81			0.81					0.81	23%
13	Oil pipeline section (rehab)	0.9	0.9	0.81																					0.81					66%
14	Road intersection/ interchange A (rehab)	0.9	0.9	0.81																			0.81							66%
15	Road intersection/ interchange B (rehab)	0.9	0.9	0.81																			0.81							66%
16	Bank (estab. Modern transaction features)	0.9	0.9	0.81						0.81				1							0.81		0.81						0.81	35%
17	Rehab of Sewage and industrial waste collection/ transmission system	0.9	0.9	0.81																			0.81							66%
18	Wastewater treatment plant (construct)	0.9	0.9	0.81						0.81		0.81		1							0.81		0.81						0.81	28%
19	Electrical power distribution line segment A (rehab)	0.9	0.9	0.81																										81%
20	Electrical power distribution line segment B (rehab)	0.9	0.9	0.81																			0.81							66%
21	Electrical power distribution line segment C (rehab)	0.9	0.9	0.81																			0.81							66%
22	Road (surfaced) segment/ vehicle bridge A (rehab)	0.9	0.9	0.81																										81%
23	Road (surfaced) segment/ vehicle bridge B (rehab)	0.9	0.9	0.81																										81%
24	Road (surfaced) segment/ vehicle bridge C (rehab)	0.9	0.9	0.81																										81%
25	Communications tower (construct)	0.9	0.9	0.81																			0.81							66%

Figure 58. Probability of Project Success Calculations.

Upon first glance of Figure 58, the casual observer must certainly wonder: Why are the probabilities of project success so low? The straightforward response is simply based on the calculations described in the preceding paragraphs, which can also be found in any textbook on probability or reliability theory, to include Lewis' text. The most unsettling statistic in Figure 58 is that the more projects that a project is dependent upon to perform properly, the lower the probability of that project's probability of success. One need only look at a project like the hospital (project #3), which is dependent upon water, power, and sewer components in order to perform properly, to see the impact of this law of probability.

While this technique may appear to be overly pessimistic, it forces decision-makers to consider the vitally important risk factors that are so often overlooked when it comes to the reconstruction of critical infrastructure projects. It is also based on a primary assumption that the likelihood of any of the events occurring are independent from one another, which might not be the case in reality. Before concluding the topic of probability of project success and project risk, it should be noted that Lewis, in *Critical Infrastructure Protection in Homeland Security*, does an excellent job of identifying and articulating several different mathematical (optimization) models that clearly demonstrate how to "buy down" levels of unacceptable risk within an entire infrastructure sector, as opposed to a single component within the sector, by re-allocating budgetary amounts. The interested reader, if primarily concerned with mitigating project risks, is encouraged to read Dr. Lewis' text (Chapter 6 addresses these types of optimization models).

	Infrastructure Project	Prob. Of Project Success
19	*Electrical power distribution line segment A (rehab)*	*81%*
22	*Road (surfaced) segment/ vehicle bridge A (rehab)*	*81%*
23	*Road (surfaced) segment/ vehicle bridge B (rehab)*	*81%*
24	*Road (surfaced) segment/ vehicle bridge C (rehab)*	*81%*
1	*Airport: Runway (rehab)*	*66%*
4	*Railroad junction/ segment of rail (rehab)*	*66%*
8	*Construction of Transmission System*	*66%*
13	*Oil pipeline section (rehab)*	*66%*
14	*Road intersection/ interchange A (rehab)*	*66%*
15	*Road intersection/ interchange B (rehab)*	*66%*
17	*Rehab of Sewage and industrial waste collection/ transmission system*	*66%*
20	*Electrical power distribution line segment B (rehab)*	*66%*
21	*Electrical power distribution line segment C (rehab)*	*66%*
25	*Communications tower (construct)*	*66%*
6	*Rehabilitation of water distribution network*	*53%*
10	*Construction of Distribution System/ Facilities*	*53%*
5	Shrine (rehab)	43%
3	Hospital (rehab)	35%
7	Rehabilitation of WTP	35%
9	Construction of Water Treatment Plant	35%
11	Construction of Reverse Osmosis (RO) Plant	35%
16	Bank (estab. Modern transaction features)	35%
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	28%
18	Wastewater treatment plant (construct)	28%
12	Oil storage facility (rehab)	23%

Figure 60. List of Probabilities of Project "Success."

Figure 61 displays individual project DEA efficiency scores and vulnerabilities.

	Infrastructure Project	DEA Efficiency	Probability of success of project
19	Electrical power distribution line segment A (rehab)	**3319.68**	81%
25	Communications tower (construct)	**1498.28**	66%
8	Construction of Transmission System	**1306.82**	66%
6	Rehabilitation of water distribution network	**1128.26**	53%
7	Rehabilitation of WTP	**1043.78**	35%
15	Road intersection/ interchange B (rehab)	**1024.20**	66%
23	Road (surfaced) segment/ vehicle bridge B (rehab)	**883.57**	81%
9	Construction of Water Treatment Plant	**819.82**	35%
10	Construction of Distribution System/ Facilities	**805.57**	53%
11	Construction of Reverse Osmosis (RO) Plant	**721.07**	35%
17	Rehab of Sewage and industrial waste collection/ transmission system	**537.67**	66%
16	Bank (estab. Modern transaction features)	**468.21**	35%
14	Road intersection/ interchange A (rehab)	**366.42**	66%
22	Road (surfaced) segment/ vehicle bridge A (rehab)	**289.55**	81%
18	Wastewater treatment plant (construct)	**238.57**	28%
24	Road (surfaced) segment/ vehicle bridge C (rehab)	**225.77**	81%
21	Electrical power distribution line segment C (rehab)	**180.24**	66%
20	Electrical power distribution line segment B (rehab)	**39.80**	66%
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	**21.98**	28%
1	Airport: Runway (rehab)	**21.93**	66%
5	Shrine (rehab)	**3.00**	43%
3	Hospital (rehab)	**1.10**	35%
12	Oil storage facility (rehab)	**0.03**	23%
4	Railroad junction/ segment of rail (rehab)	**0.00**	66%
13	Oil pipeline section (rehab)	**0.00**	66%

Figure 61. DEA Model Results, Ranked on the Basis of Efficiency, of Critical Infrastructure Component Projects with Corresponding Project Risks.

Note: Projects shaded are those that are deemed to be DEA efficient, yet have risk levels that fall below the "Pareto threshold."

Determining Project Interactions and Accumulation Effects

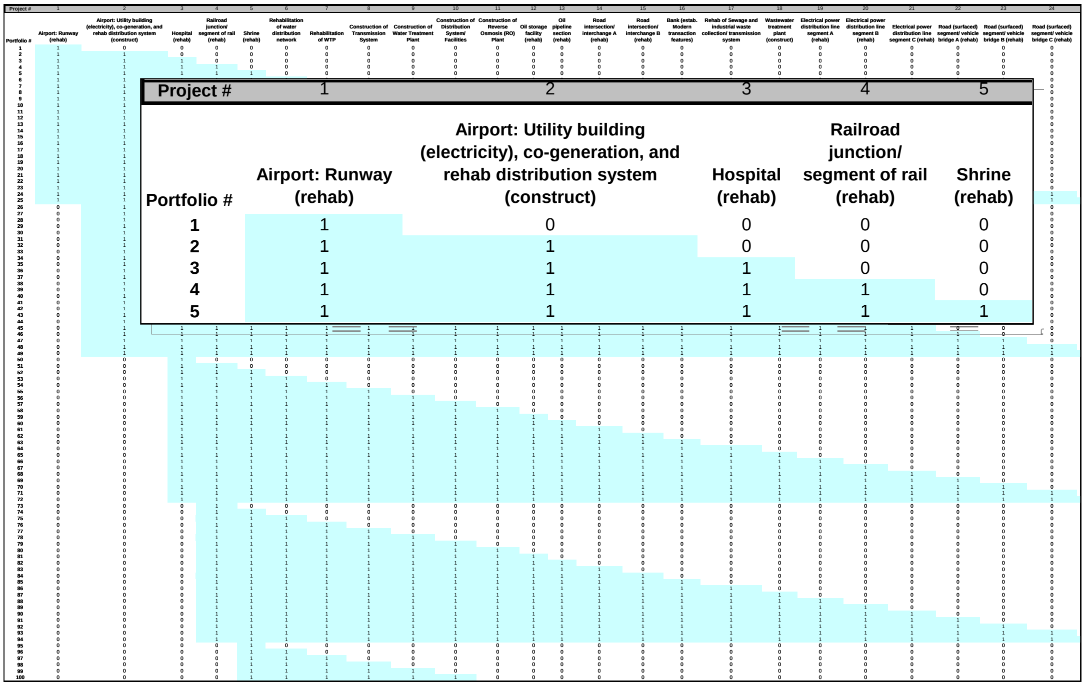
Before starting the next section on portfolio generation, it is important to introduce one of the most significant contributions made by Eilat, et al., namely, the notion of project interactions and accumulation effects. While the two-dimensional matrix limits the ability to model higher order interactions and effects, since one can show costs and benefits associated with two distinct projects, but not the impact of three distinct projects, one need only consider the sage of design of experiments, Douglas Montgomery, to make the assumption that anything larger than a second-order effect can usually be ignored as being insignificant (when compared to the magnitude of the primary (main) effects). Therefore, it turns out that, due to accumulation and dependency factors being accounted for as part of the raw data matrices within the DEA model, the resource (input) interaction matrices, U^i, have relatively little impact on the generation of portfolios. However, the value interaction matrix of benefits (outputs), V^r, which accounts for both outputs and probabilities of project success, as will be demonstrated in the next section, is significant. Figure 62 shows one of the resource (input) interaction matrices.

	Infrastructure Project	Airport: Runway (rehab) 1	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct) 2	Hospital (rehab) 3	Railroad junction/ segment of rail (rehab) 4	Shrine (rehab) 5	Rehabilitation of water distribution network 6	Rehabilitation of WTP 7	Construction of Transmission System 8	Construction of Water Treatment Plant 9	Construction of Distribution System/ Facilities 10	Construction of Reverse Osmosis (RO) Plant 11	Oil storage facility (rehab) 12	Oil pipeline section (rehab) 13	Road intersection/ interchange A (rehab) 14	Road intersection/ interchange B (rehab) 15	Bank (estab. Modern transaction features) 16	Rehab of Sewage and industrial waste collection/ transmission system 17	Wastewater treatment plant (construct) 18	Electrical power distribution line segment A (rehab) 19	Electrical power distribution line segment B (rehab) 20	Electrical power distribution line segment C (rehab) 21	Road (surfaced) segment/ vehicle bridge A (rehab) 22	Road (surfaced) segment/ vehicle bridge B (rehab) 23	Road (surfaced) segment/ vehicle bridge C (rehab) 24	Communications tower (construct) 25
1	Airport: Runway (rehab)	1.5																								
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)		0.55																							
3	Hospital (rehab)			0.667																						
4	Railroad junction/ segment of rail (rehab)				0.025																					
5	Shrine (rehab)					0.0003																				
6	Rehabilitation of water distribution network			-0.1			1.055																			
7	Rehabilitation of WTP			-0.05				0.365																		
8	Construction of Transmission System								2.22																	
9	Construction of Water Treatment Plant			-0.05						5.62																
10	Construction of Distribution System/ Facilities			-0.1			-0.5				3.265															
11	Construction of Reverse Osmosis (RO) Plant											7.95														
12	Oil storage facility (rehab)												4													
13	Oil pipeline section (rehab)													0.4												
14	Road intersection/ interchange A (rehab)														1.5											
15	Road intersection/ interchange B (rehab)															1.5										
16	Bank (estab. Modern transaction features)																0.025									
17	Rehab of Sewage and industrial waste collection/ transmission system																	0.22								
18	Wastewater treatment plant (construct)																		1.52							
19	Electrical power distribution line segment A (rehab)			-0.01																0.005						
20	Electrical power distribution line segment B (rehab)																				0.005					
21	Electrical power distribution line segment C (rehab)																					0.005				
22	Road (surfaced) segment/ vehicle bridge A (rehab)																						0.053333333			
23	Road (surfaced) segment/ vehicle bridge B (rehab)																							0.053333333		
24	Road (surfaced) segment/ vehicle bridge C (rehab)																								0.025	
25	Communications tower (construct)																-0.01									0.025

Figure 62. Interaction Matrix for Input #1 (New Construction Budget).

<u>Generating Portfolios</u>

The next step of the analysis was to combine the twenty five original projects (n_p $= 25$) in over 2600 possible ways ($\sum z_k$ = 2602) in order to develop portfolios.



Project #	1	2	3	4	5
Portfolio #	Airport: Runway (rehab)	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	Hospital (rehab)	Railroad junction/ segment of rail (rehab)	Shrine (rehab)
1	1	0	0	0	0
2	1	1	0	0	0
3	1	1	1	0	0
4	1	1	1	1	0
5	1	1	1	1	1

Figure 63. The First 100 Portfolios of Projects are Shown as they Appear in MS Excel© (background), Along with an Enlarged Version (inset).

As stated previously in Chapter 3, if a project was contained within the portfolio, z_k, it was represented by a 1 in the 1 x 25 horizontal array (row) of cells, otherwise, the value of the cell was 0. Furthermore, each portfolio of projects (z_k) was then multiplied by the 25 x 25 U^i interaction matrix, whose product was multiplied by the transpose of z_k (indicated as z_k^T), to yield the scalar product of $\hat{x}_{1k}$. The number associated with $\hat{x}_{1k}$ is just the amount of resources (Input #1, or new construction budget) that are required in order to undertake successfully each of the projects contained within a particular portfolio, z_k. The figure below depicts the results of this computation, and also indicates the assumed resource constraints (i.e. "Input 1 Available").

Portfolio #	x-hat$_{1k}$	x-hat$_{1k}$ (adjusted for life cycle)	Input 1 Available
1	1.50	30.00	200
2	2.05	41.00	200
3	2.72	81.00	200
4	2.74	82.00	200
5	2.74	82.02	200
6	3.70	103.12	200
7	4.01	110.42	200
8	6.23	199.22	200
9	11.80	367.82	200
10	14.47	498.42	200

Figure 64. Sample of Portfolio Input Results.

Recall from Chapter 3 that the term "*x-hat$_{1k}$*" (shown symbolically as $\hat{x}_{1k}$) is the total amount of the "new construction" budget that is required to successfully undertake all of the projects contained within a particular portfolio. Shaded cells indicate portfolios that violate the first constraint. Furthermore, it should be noted that constraint right-hand-side values were estimated, and rounded up to 200, from a 2008 GAO report on capital project expenditures. See Figures 65 and 66 on the following pages.

Dollars in millions

Province	2006 Provincial capital projects budgets Budget allocation	Amount committed	Percentage of budget committed	Amount spent	Percentage of budget spent
Anbar	$97	$78	80%	$78	80%
Babil	111	111	100	98	88
Baghdad	503	503	100	427	85
Basrah	172	172	100	115	67
Dhi-Qar	119	119	100	119	100
Diyala	99	61	62	0	0
Karbala	62	56	90	56	90
Kurd Prov	131	126	96	35	27
Maysan	66	66	100	50	76
Muthana	46	43	93	39	85
Najaf	79	72	91	72	91
Ninawa	202	202	100	202	100
Qadisiyah	74	74	100	56	76
SaD	83	82	99	65	78
Tameen	81	81	100	73	90
Wasit	74	72	97	60	81
Total	**$1,999**	**$1,918**	**96%**	**$1,543**	**77%**

Source: U.S. Embassy reporting of unofficial data collected by PRTs.

Dollars in millions

Province	2007 Provincial capital projects budgets Budget allocation	Amount committed	Percentage of budget committed	Amount spent	Percentage of budget spent
Anbar	$107	$52	49%	$0	0%
Babil	112	127	113	42	38
Baghdad	560	301	54	70	13
Basrah	195	159	82	12	6
Dhi-Qar	138	119	86	2	1
Diyala	110	0	0	0	0
Karbala	71	62	86	17	24
Kurd Prov	314	113	36	0	0
Maysan	76	2	3	26	34
Muthana	52	38	73	4	8
Najaf	88	88	100	23	26
Ninawa	226	54	24	17	8
Qadisiyah	64	64	100	13	20
SaD	93	75	81	11	12
Tameen	90	58	64	17	19
Wasit	83	65	78	20	24
Total	**$2,381**	**$1,379**	**58%**	**$275**	**12%**

Source: U.S. Embassy reporting of unofficial data collected by PRTs.

Note: The data include $314 million of Kurdistan region's separate 2007 capital projects allocation of $1.56 billion. The total 2007 budget allocation for the provinces, excluding the Kurdistan region, is $2.067 billion.

Figure 65. GAO Report on "Capital Projects" (i.e. New Construction) Budget Allocation (Input #1) for Iraqi Provinces.

Source: Government Accountability Office, *Iraq Reconstruction: Better Data Needed to Assess Iraq's Budget Execution* (Washington D.C.: Government Accountability Office, 15 January 2008), 31 – 32.

Figure 66 provides a sample of the portfolio roll-up. Of interest is the fact that of over 2600 portfolios generated, only twenty two percent of them (581) were feasible based on their ability to satisfy given budget constraints. It should be noted that these results were produced prior to value interaction matrix of benefits (outputs) being generated. Therefore, based solely off of resource (input) availability, the model eliminated over three quarters of the possible portfolios.

Portfolio #	x-hat$_{1k}$	x-hat$_{2k}$	x-hat$_{3k}$	Feasible?
1	30.00	3.00	3.00	FEASIBLE
2	41.00	4.75	4.55	FEASIBLE
3	81.00	14.75	14.55	FEASIBLE
4	82.00	14.85	14.65	FEASIBLE
5	82.02	14.85	14.65	FEASIBLE
6	103.12	20.13	18.87	NOT
7	110.42	21.95	20.60	NOT
8	199.22	44.15	38.26	NOT
9	367.82	86.30	80.31	NOT
10	498.42	113.95	106.33	NOT

# of Feasible Portfolios *(as a function of input availability)*
581

% of Feasible Portfolios *(as a function of input availability)*
22%

Figure 66. Sample and Summary of Portfolio Results Based Solely on Input Type Availability.

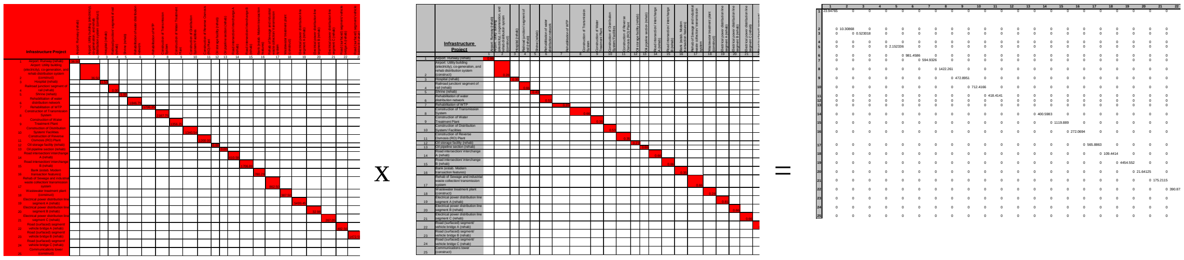
Figure 67 shows the number of times that each of the individual projects appears in one of the feasible portfolios. Not surprisingly, projects that are least expensive tend to appear most frequently. However, one of the interesting, and potentially problematic, results of the analysis is the absence of several important infrastructure projects from any of the 581 feasible portfolios (see Figure 67). Furthermore, upon closer inspection of the data in Excel, it appears that each of the projects that were omitted from a single portfolio (save Project 11, RO Plant), were in violation of the twenty million annual budget for protection/ security. Given the level of importance placed upon projects eight through

ten, due to the fact that they are related to water quality and availability, this issue will be considered further within the sensitivity analysis section of this chapter. Before continuing, it is important to note that at this stage of the portfolio evaluation, there has not been an additional optimization (DEA) iteration, the second optimization iteration will be completed after the enumeration and analysis of outputs is complete.

	Project	# of Times Project Appears in a Feasible Portfolio
1	Airport: Runway (rehab)	52
2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	83
3	Hospital (rehab)	98
4	Railroad junction/ segment of rail (rehab)	117
5	Shrine (rehab)	117
6	Rehabilitation of water distribution network	99
7	Rehabilitation of WTP	66
8	Construction of Transmission System	0
9	Construction of Water Treatment Plant	0
10	Construction of Distribution System/ Facilities	0
11	Construction of Reverse Osmosis (RO) Plant	0
12	Oil storage facility (rehab)	0
13	Oil pipeline section (rehab)	57
14	Road intersection/ interchange A (rehab)	92
15	Road intersection/ interchange B (rehab)	130
16	Bank (estab. Modern transaction features)	155
17	Rehab of Sewage and industrial waste collection/ transmission system	162
18	Wastewater treatment plant (construct)	155
19	Electrical power distribution line segment A (rehab)	179
20	Electrical power distribution line segment B (rehab)	186
21	Electrical power distribution line segment C (rehab)	191
22	Road (surfaced) segment/ vehicle bridge A (rehab)	189
23	Road (surfaced) segment/ vehicle bridge B (rehab)	174
24	Road (surfaced) segment/ vehicle bridge C (rehab)	141
25	Communications tower (construct)	88

Figure 67. The Number of Times that Each of the Projects Appears in a Feasible Portfolio. *Note:* Projects 8 -10 and 12 are absent from any feasible portfolio.

The next step is to calculate the value interaction matrix of benefits (outputs). This is done by performing the simple matrix multiplication steps indicated in Figure 68.



Output #1 Interaction Matrix, V^1

Probabilities of Project Success Matrix, P

Output #1 Expected value (EV) Interaction matrix, B^1

Figure 68. Incorporating Vulnerabilities (Risk) to Arrive at the Expected Outputs (Benefits) of the Various Projects.

The point to make at this stage is to note that since dependencies are already accounted for explicitly by the MOEs (outputs) in the individual project (DEA) model, the contents of the output interaction matrices, V^r, are identical to the parameters contained within the original DEA model (see Figure 53 or 55).

Portfolio #	y-hat$_{1k}$
1	23.95
2	34.26
3	34.78
4	34.78
5	36.93
6	1018.39
7	1613.32
8	3035.58
9	3508.48
10	4220.90

Figure 69. Incorporating Probability of Project Success to Arrive at the Expected Outputs (Benefits) of the Various Projects.

Portfolio Analysis Results

Figures 70 and 71 provide an example and summary, respectively, of the initial portfolio analysis results of the 581 feasible portfolios (see Figure 66).

Portfolio	Input			Input	Output			Output	Weighted	DEA
#	x-hat$_{1k}$	x-hat$_{2k}$	x-hat$_{3k}$	Weight	y-hat$_{1k}$	y-hat$_{2k}$	y-hat$_{3k}$	Weight	Difference	Efficiency
1	30.00	3.00	3.00	61.8246	23.95	0.11	0.00	0.0019	-61.82	0.01
2	41.00	4.75	4.00	75.6286	34.26	0.22	0.00	0.0027	-75.63	0.01
3	81.00	14.75	8.00	76.2474	34.78	0.57	0.00	0.0028	-76.24	0.00
4	82.00	14.85	8.10	78.3082	34.78	0.59	0.00	0.0028	-78.31	0.00
5	82.02	14.85	8.10	78.3391	36.93	0.59	0.00	0.0029	-78.34	0.00
26	11.00	2.75	1.10	0.17016	10.31	0.11	0.00	0.0008	-0.17	0.01
27	51.00	12.75	5.10	0.78894	10.83	0.46	0.00	0.0009	-0.79	0.00
28	52.00	12.85	5.20	2.84976	10.83	0.47	0.00	0.0009	-2.85	0.00
29	52.02	12.85	5.20	2.88067	12.98	0.48	0.00	0.0011	-2.88	0.00
30	73.12	18.13	7.31	3.20707	994.44	0.97	106.29	0.0861	-3.12	0.03
31	80.42	19.95	7.94	3.31821	1589.38	1.03	176.02	0.138	-3.18	0.05
50	40.00	10.00	4.00	0.61877	0.52	0.35	0.00	7E-05	-0.62	0.00
51	41.00	10.10	4.10	2.67959	0.52	0.37	0.00	7E-05	-2.68	0.00
52	41.02	10.10	4.10	2.71051	2.68	0.38	0.00	0.0002	-2.71	0.00
53	62.12	15.38	6.21	3.03691	984.13	0.86	106.29	0.0853	-2.95	0.04
54	69.42	17.20	6.84	3.14804	1579.07	0.92	176.02	0.1372	-3.01	0.06
75	22.12	5.38	2.21	2.41814	983.61	0.51	106.29	0.0852	-2.33	0.11
76	29.42	7.20	2.84	2.52927	1578.54	0.56	176.02	0.1372	-2.39	0.13
96	21.12	5.28	2.11	0.35732	983.61	0.49	106.29	0.0852	-0.27	0.24

Figure 70. Portfolio DEA Efficiency Scores.

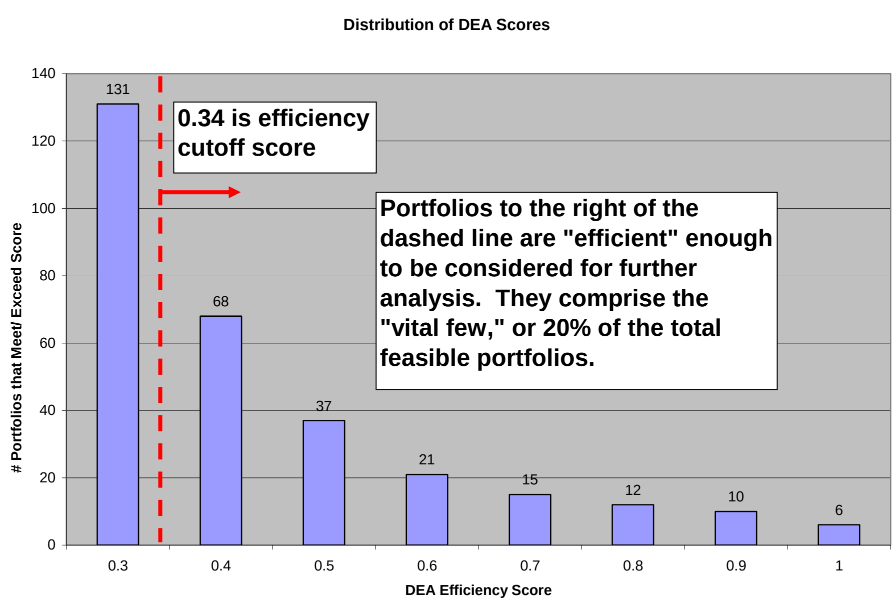


Figure 71. Distribution of DEA Scores.

Of note was the low efficiency scores of the portfolios in Figure 71 (i.e. only 131 portfolios exceeded a DEA efficiency of thirty percent). This called for further analysis, but before doing so, it was necessary to conduct another “Pareto Analysis” and identify where the eighty percent of the overall portfolio value, according to Pareto, was coming from. A quick way to do this was to simply take twenty percent of 484, which yielded 96.8. From Figure 71, one can observe that 96.8 (on the y-axis) falls somewhere between 0.30 and 0.40 DEA efficiency. Therefore, 0.34 was established as the threshold for DEA efficiency so that any project with a DEA efficiency score higher than 0.34 would be considered for further analysis. Thus, further analysis needed to be done on the 96 portfolios that occurred above this threshold.

This further analysis resulted in a distribution of the infrastructure projects that were included within the 96 remaining portfolios (see Figure 72). Figure 73 simply shows a sample of the portfolio compositions.

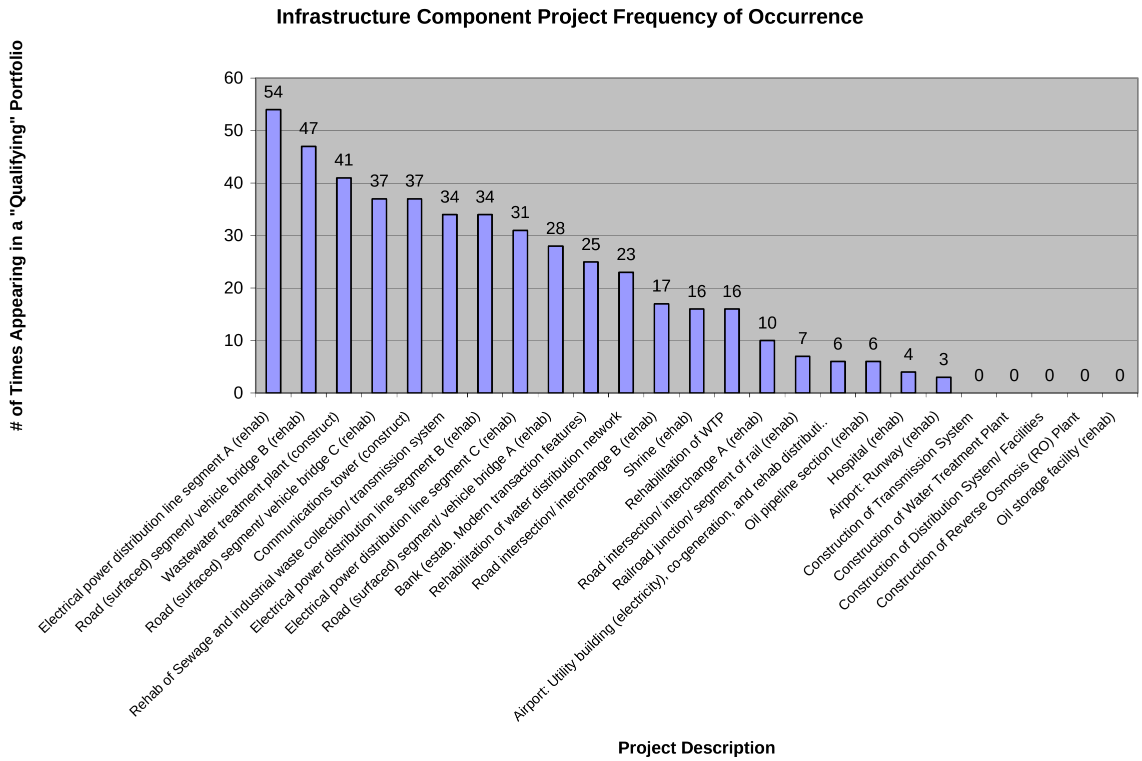
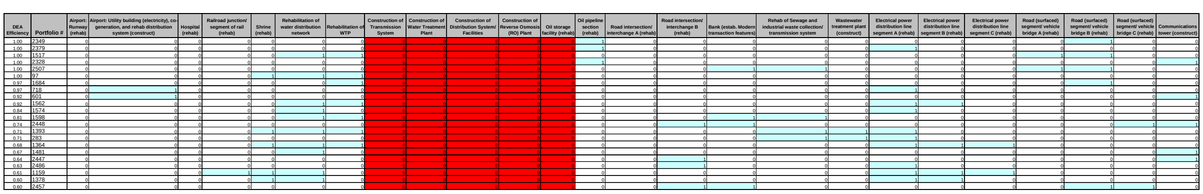


Figure 72. Distribution of Individual Infrastructure Projects within the 96 "Qualifying" Portfolios.



DEA Efficiency	Portfolio #	Airport: Runway (rehab)	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	Hospital (rehab)	Railroad junction/ segment of rail (rehab)	Shrine (rehab)	Rehabilitation of water distribution network	Rehabilitation of WTP	Construction of Transmission System	Construction of Water Treatment Plant
1.00	2349	0	0	0	0	0	0	0	0	0
1.00	2379	0	0	0	0	0	0	0	0	0
1.00	1517	0	0	0	0	0	1	1	0	0
1.00	2328	0	0	0	0	0	0	0	0	0
1.00	2507	0	0	0	0	0	0	0	0	0
1.00	97	0	0	0	0	1	1	1	0	0

Figure 73. Sample of Portfolio Composition, Sorted by DEA Efficiency, of the 96 "Qualifying" Portfolios.

Before continuing, it is important to introduce the notion of an "efficient frontier." In simple terms, this frontier is the edge of the graph, along which can be found, those portfolios that provide the greatest value for one's investment of resources. For engineers and scientists, it is fairly standard to conduct a plot of cost versus benefit, risk versus reward, and stress versus load in order to identify those units that are most efficient. Furthermore, given that the DEA model performs this calculation explicitly via optimization, one would expect there to be little deviation between the DEA model results, and a simple plot of weighted outputs vs. weighted inputs. With this in mind, those portfolios out of the "96 qualifying" that had a DEA efficiency score of 1.0, would generally be expected to fall along the efficient frontier of a simple plot. However, this did not turn out to be the case (see Figures 74 and 75). One can speculate as to the lack of the DEA model's ability to find an "optimal solution," that was obtained relatively easily via brute force enumeration. In any event, the portfolios that fell along the efficient frontier, regardless of DEA efficiency score, were the ones analyzed further via sensitivity analysis. Figure 76 shows the histogram of project frequency within the "efficient" portfolios.

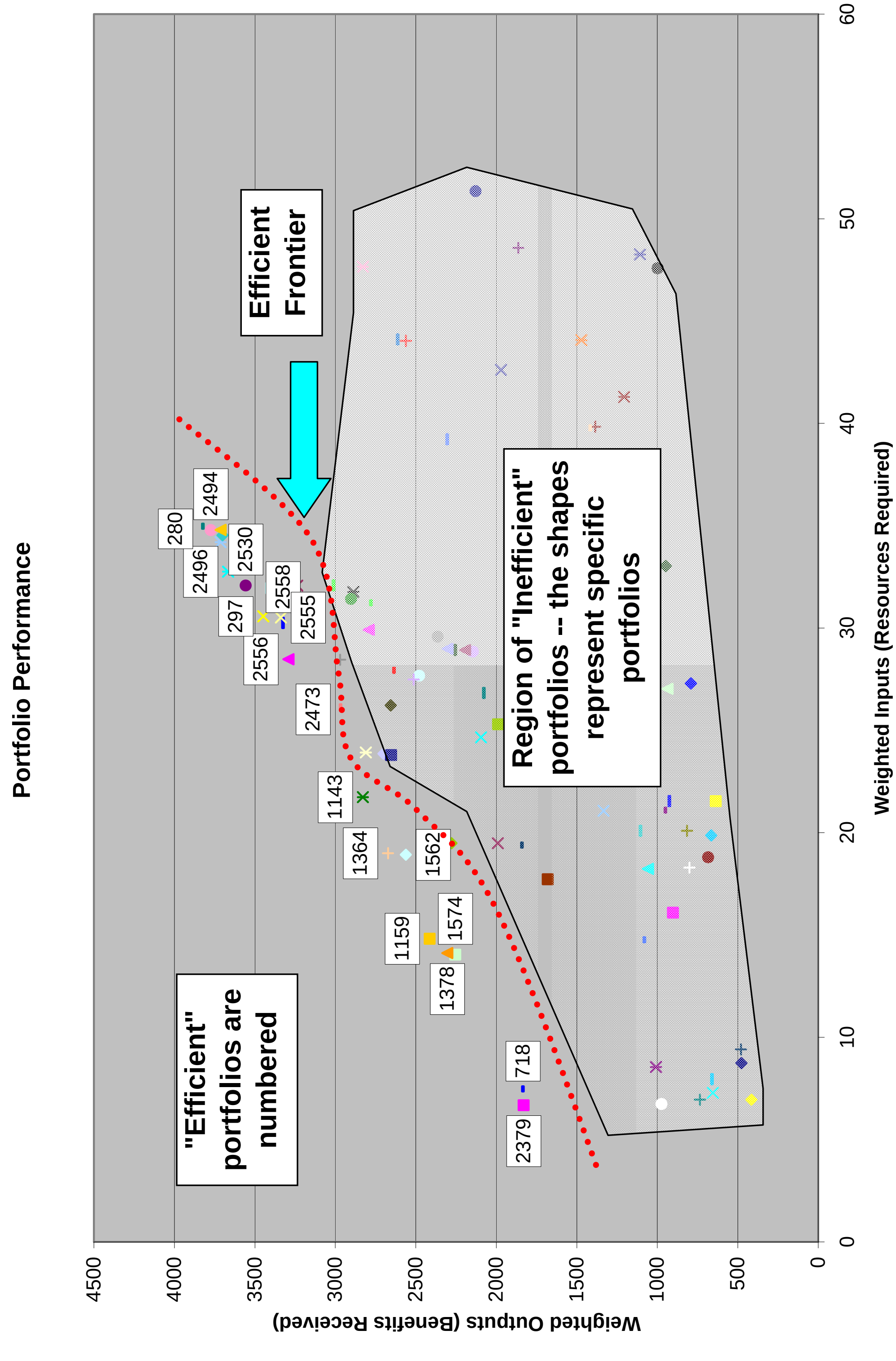


Figure 74. Weighted Outputs versus Weighted Inputs of 96 “Qualifying Projects” to Verify the Efficient Frontier.

	Portfolio #	DEA Efficiency	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	Railroad junction/ segment of rail (rehab)	Shrine (rehab)	Rehabilitation of water distribution network	Rehabilitation of WTP	Oil pipeline section (rehab)	Road intersection/ interchange A (rehab)	Road intersection/ interchange B (rehab)	Bank (estab. Modern transaction features)	Rehab of Sewage and industrial waste collection/ transmission system	Wastewater treatment plant (construct)	Electrical power distribution line segment A (rehab)	Electrical power distribution line segment B (rehab)	Electrical power distribution line segment C (rehab)	Road (surfaced) segment/ vehicle bridge A (rehab)	Road (surfaced) segment/ vehicle bridge B (rehab)	Road (surfaced) segment/ vehicle bridge C (rehab)	Communications tower (construct)
Least Expensive Option	2379	1.00	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
	718	0.97	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	1562	0.92	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0
	1574	0.84	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	1364	0.68	0	0	1	1	1	0	0	0	0	0	0	1	1	1	0	0	0	0
	1159	0.61	0	1	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0
	1378	0.60	0	0	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0
	1143	0.48	0	1	1	1	1	0	0	0	0	0	0	1	1	1	1	0	0	0
	2331	0.48	0	0	0	0	0	1	1	1	1	0	0	0	0	0	1	1	1	1
	2473	0.44	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	0	0	0
	2556	0.42	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1
	297	0.41	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
	2496	0.41	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	1	1
	2530	0.41	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1	1
	280	0.40	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
	2558	0.40	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1
	2555	0.40	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1
Most Expensive (Feasible) Option	2494	0.40	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	1

	Portfolio #	DEA Efficiency	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)	Railroad junction/ segment of rail (rehab)	Shrine (rehab)	Rehabilitation of water distribution network	Rehabilitation of WTP
Least Expensive Option	2379	1.00	0	0	0	0	0
	718	0.97	1	0	0	0	0
	1562	0.92	0	0	0	1	1
	1574	0.84	0	0	0	1	0
	1364	0.68	0	0	1	1	1
	1159	0.61	0	1	1	1	0
	1378	0.60	0	0	1	1	0
	1143	0.48	0	1	1	1	1
	2331	0.48	0	0	0	0	0
	2473	0.44	0	0	0	0	0
	2556	0.42	0	0	0	0	0
	297	0.41	0	0	0	0	0
	2496	0.41	0	0	0	0	0
	2530	0.41	0	0	0	0	0
	280	0.40	0	0	0	0	0
	2558	0.40	0	0	0	0	0
	2555	0.40	0	0	0	0	0
Most Expensive (Feasible) Option	2494	0.40	0	0	0	0	0

Figure 75. A Partial List of Projects Constituting the Eighteen "Efficient" Portfolios.

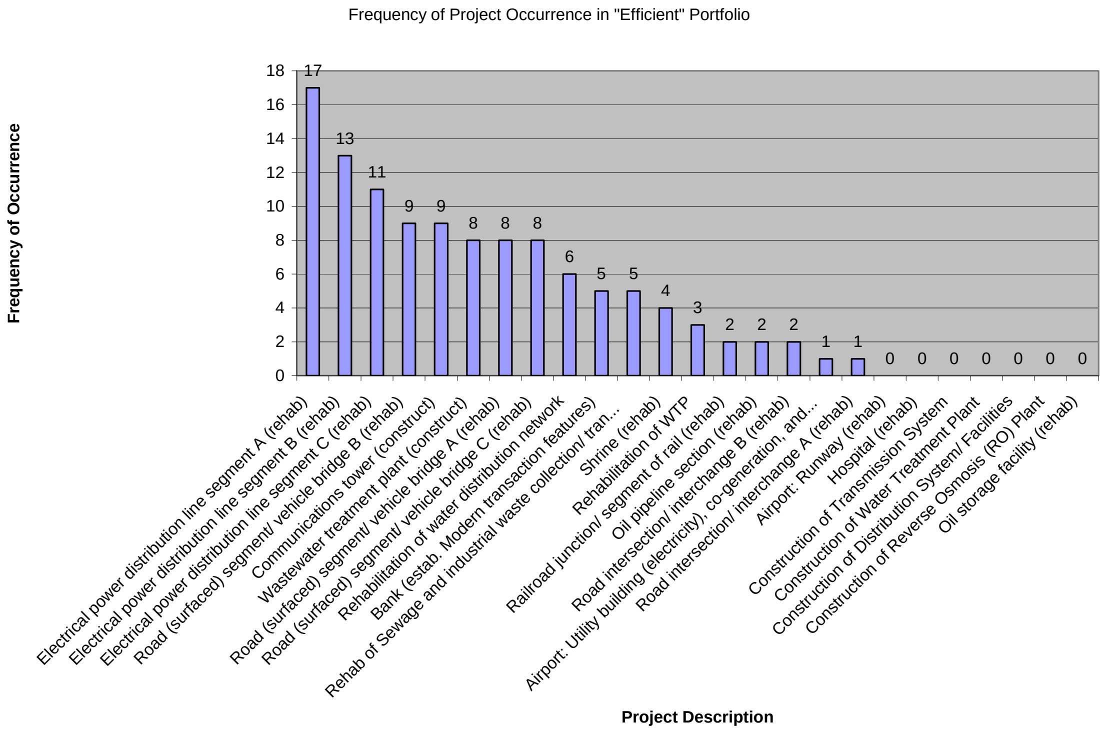


Figure 76. Frequency of Projects Occurring in the Efficient Portfolios.

Figure 77 shows those projects that are not included in any of the "efficient" portfolios. As stated previously, one of the glaring omissions from the list of efficient, and feasible, portfolios is the construction of the water transmission system (Project #8). By extension, any decision-maker faced with the dilemma of being compelled to undertake one of these projects must find a way to either reduce costs associated with the project (inputs), improve benefits associated with the project (outputs), or improve the probability of project success.

Project #	Description
1	Airport Runway
3	Hospital
8	Construction of Transmission System
9	Construction of Water Treatment Plant
10	Construction of Distribution System/ Facilities
11	Construction of RO Plant
12	Oil storage facility

Figure 77. Projects Not Represented Within Any of the Portfolios Along the "Efficient Frontier."

Sensitivity Analysis

As alluded to previously, one of the attractive features of considering portfolios instead of just individual projects is that decision-makers are able to select from among a range of possible "efficient" portfolios in order to select the portfolio that best satisfies the needs of affected stakeholders. This is an especially attractive option for a decision-maker given the dynamic nature of stability operations environments and will be demonstrated in this section's discussion of sensitivity analysis. To facilitate this discussion, one must consider several likely courses of action (COA) that might occur during the policy-recommendation process:

COA #1: Focus on the most (or least) expensive option.

COA #2: Focus on providing the bare "essential services" (e.g. water and electricity).

COA #3: Focus on maximizing the number of people served.

COA #4: Focus on ensuring that one of the "infeasible" projects gets approved.

Portfolios greatly facilitate this COA analysis since, in theory, one can simply take any of the "efficient" portfolios that best support the decision-maker's intent. However, before attempting to address how to respond to various COAs posed by a decision-maker, it is necessary to understand the impact upon a recommended solution should one of the major parameters be modified for some reason. In order to identify the major parameters that may be of interest in subsequent analysis, the Department of Systems Engineering at the United States Military Academy instructs its cadets to construct "stacked-bar charts" consisting of the constituent parts of its inputs (Figure 78) and outputs (Figure 79).

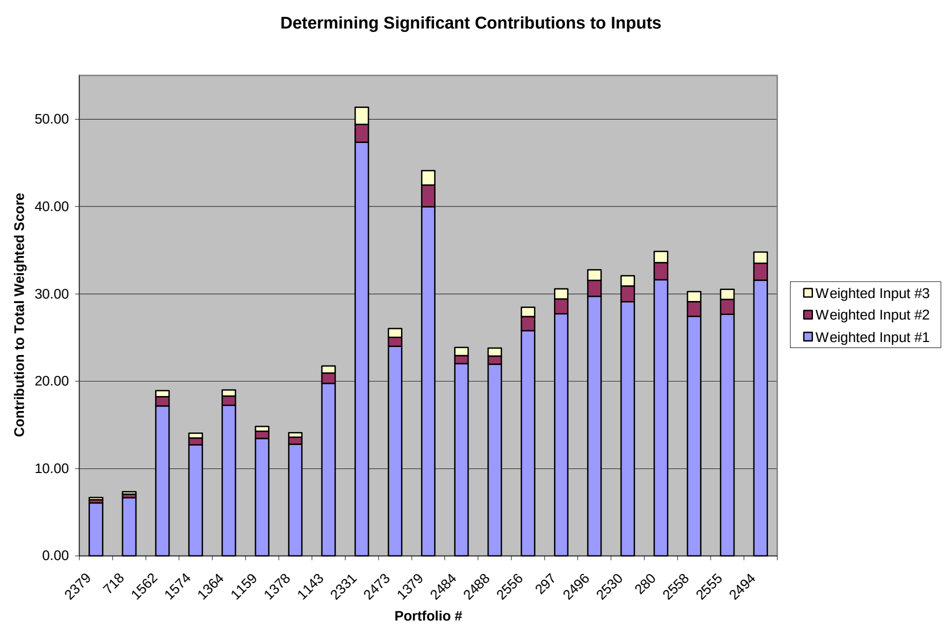


Figure 78. Stacked-Bar Chart Used to Determine Input Contribution to the Overall Weighted Input Score.

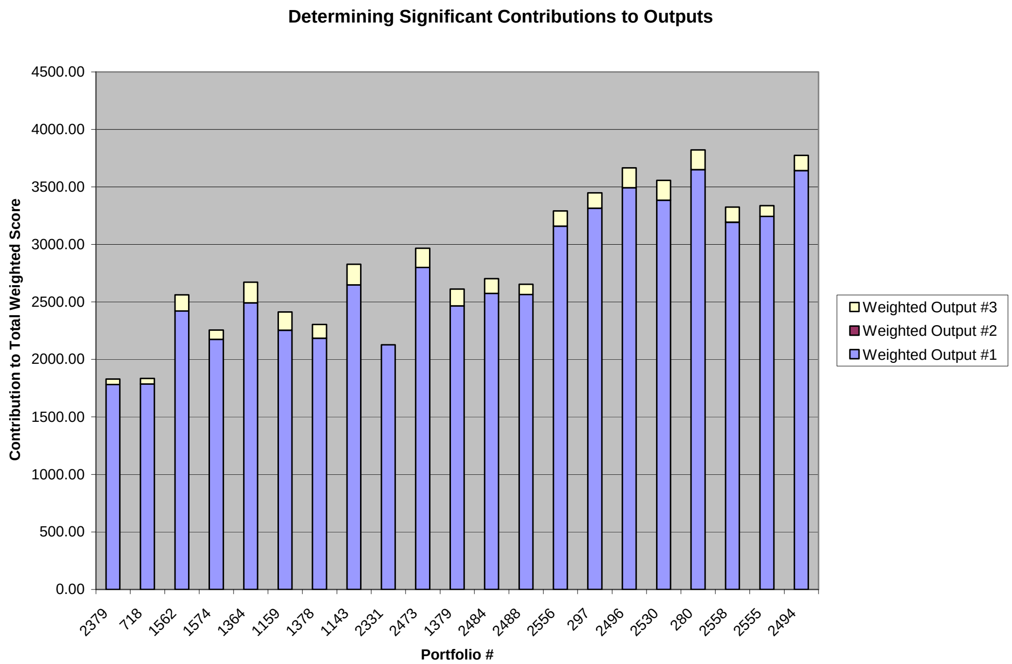


Figure 79. Stacked-Bar Chart Used to Determine Output Contribution to the Overall Weighted Output Score.

By inspection of Figure 78, one can see that the primary contributor to the total weighted input score is the weighted input value for Input #1 (The New Construction/ Capital Improvement Cost). While this weighted input value includes both the value $\left(\hat{x}_{ik}\right)$ and the weight, this sensitivity analysis will consider just the raw budget cost (Input #1), initially, in order to determine if subsequent analysis is even necessary. Furthermore, keeping in mind that the parameter of interest is a portfolio input value, which consists of multiple project inputs, the question remains as to which individual project input (x_{1j}) should be adjusted in order to determine sensitivity?

A likely candidate for this subsequent analysis would be the project that appeared most frequently in the efficient portfolios. After a quick inspection of Figure 76, it

appears that since Project 19 (Electrical power distribution line segment A (rehab)), appears seventeen times within the efficient portfolios, it would be a logical candidate on which to perform this sensitivity analysis. The next step involved in sensitivity analysis is to modify parameter values by a certain amount, typically plus or minus ten percent of the original value. However, given the degree of variability associated with parameter values in a stability operations environment, the analysis involved changing the value of Project nineteen's new construction cost ($x_{1,\ 19}$) by plus or minus twenty five percent of its original value, and plotting this as the independent variable, against the Input-Output ratio scores of three, broadly representative portfolios as the dependent variable. The resulting plot is the graph that appears in Figure 80. For the record, it should be noted that the reason only three broadly representative portfolios were selected for conducting sensitivity analysis was in order to prevent an overly congested graph. These portfolios include:

#2379 (*which contains only one other project besides Project #19)*;
#1143 (*which contains several projects in addition to Project #19)*;
#2331 (*which is the only portfolio that does not contain Project #19)*;

By inspection, it appears that none of the portfolios are sensitive to major (+/- 25%) adjustments in Project 19's New Construction Cost (Input #1). By extension, if one wanted to elicit change in the portfolio results, this is not a parameter that one would want to modify unless one is fairly certain that the estimation error exceeds +/- 25%, which is unlikely. Therefore, the recommendation to in invest in a portfolio containing Project #19 is considered to be insensitive to changes in its new construction cost

parameter values. This resulting analysis would, in turn, offer a sense of certainty to the decision-maker that this is a sound recommendation.

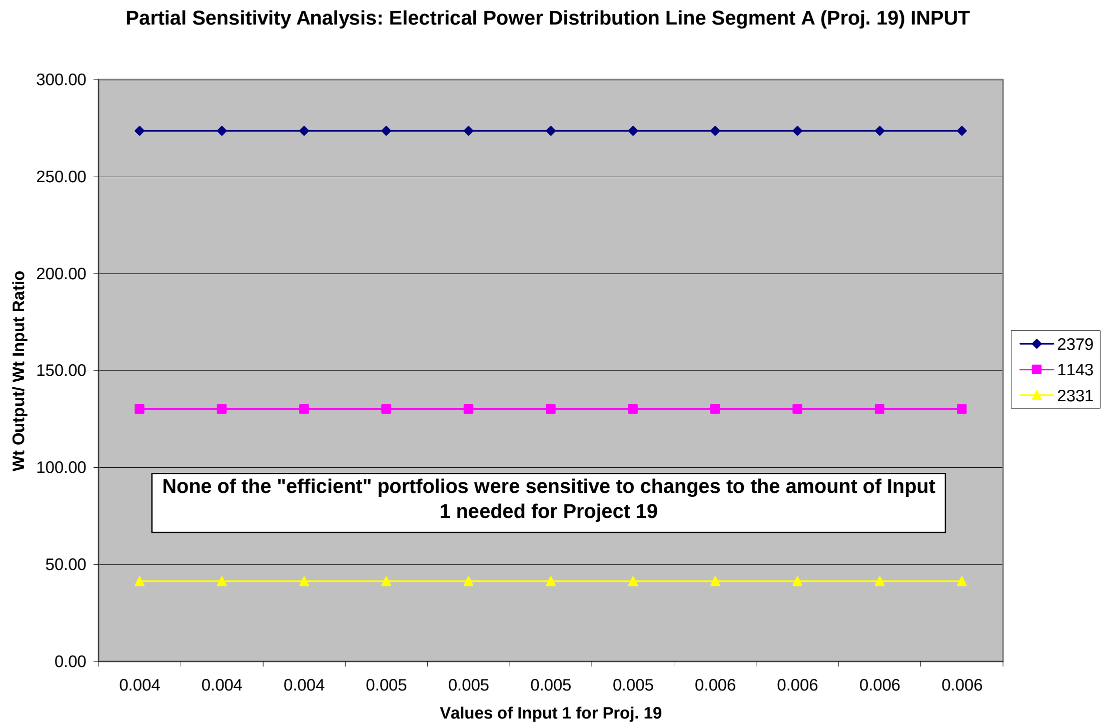


Figure 80. Sensitivity Analysis for Project #19's Input #1 Value.

The next parameter to be considered is $(\hat{y}_{rk})$ and by extension, project #19's output #1 value (Average number of people served per month) $y_{1,\,19}$. A graph of this sensitivity analysis result is shown in Figure 81. However, unlike the input parameter value just analyzed, one can see that all but one of the portfolios are sensitive to changes in this value, that is to say the portfolio that does not contain Project #19. Therefore, great care must be taken during the data gathering process to ensure that this value is precise, particularly if the recommended portfolio is going to include this particular project.

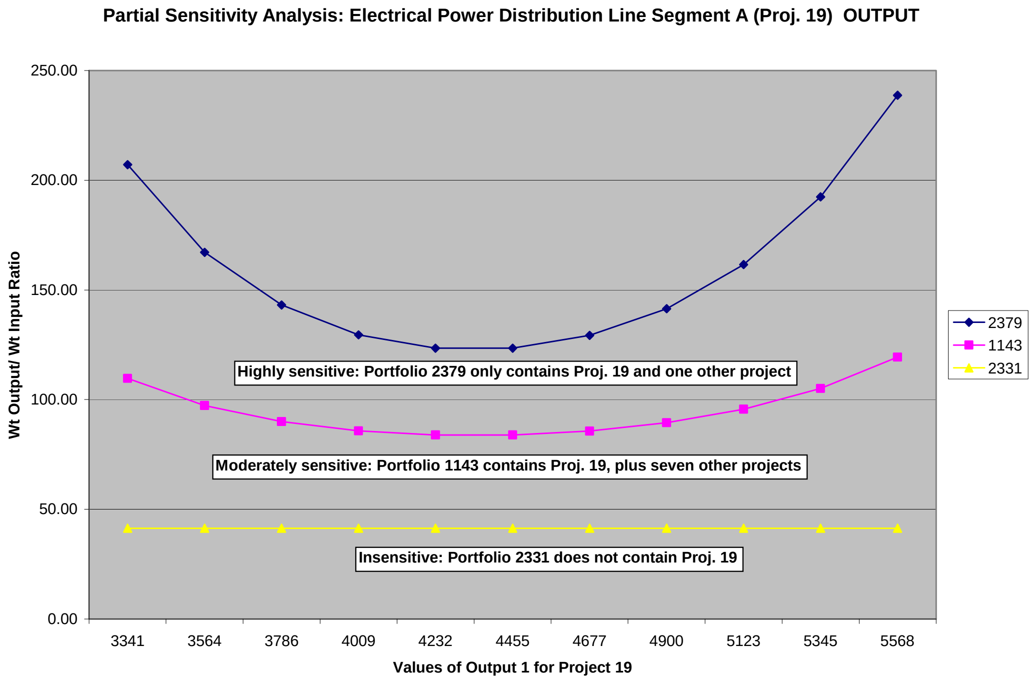


Figure 81. Sensitivity Analysis for Project #19's Output #1 Value.

Furthermore, given the magnitude of importance of the first input measure and the first output measure, it would be interesting to determine if there is a relationship between these particular parameter values, and the number of times that an individual project is likely to appear in an "efficient" portfolio? The purpose of such an analysis is to determine if one is able to predict portfolio composition based on the aforementioned, dominant parameter values. This is particularly importance since, based solely on observation, it appears that inexpensive projects tend to be over-represented in efficient portfolios, regardless of the level of output that they provide, whereas expensive projects, regardless of the level of output that they provide, tend to be under-represented.

Figure 82 attempts to demonstrate whether a relationship of the aforementioned nature exists between Input #1, New Construction Cost, and the number of times that an

individual project is likely to appear in an efficient portfolio. Given that an R^2 value of 1.0 indicates a perfect fit of a line to experimental data, the R^2 value in the figure shown below indicates that there are several projects that have very small costs associated with them, yet they were still not selected for inclusion in many portfolios. Therefore, this single variable, Input #1 value, may not offer the best explanation.

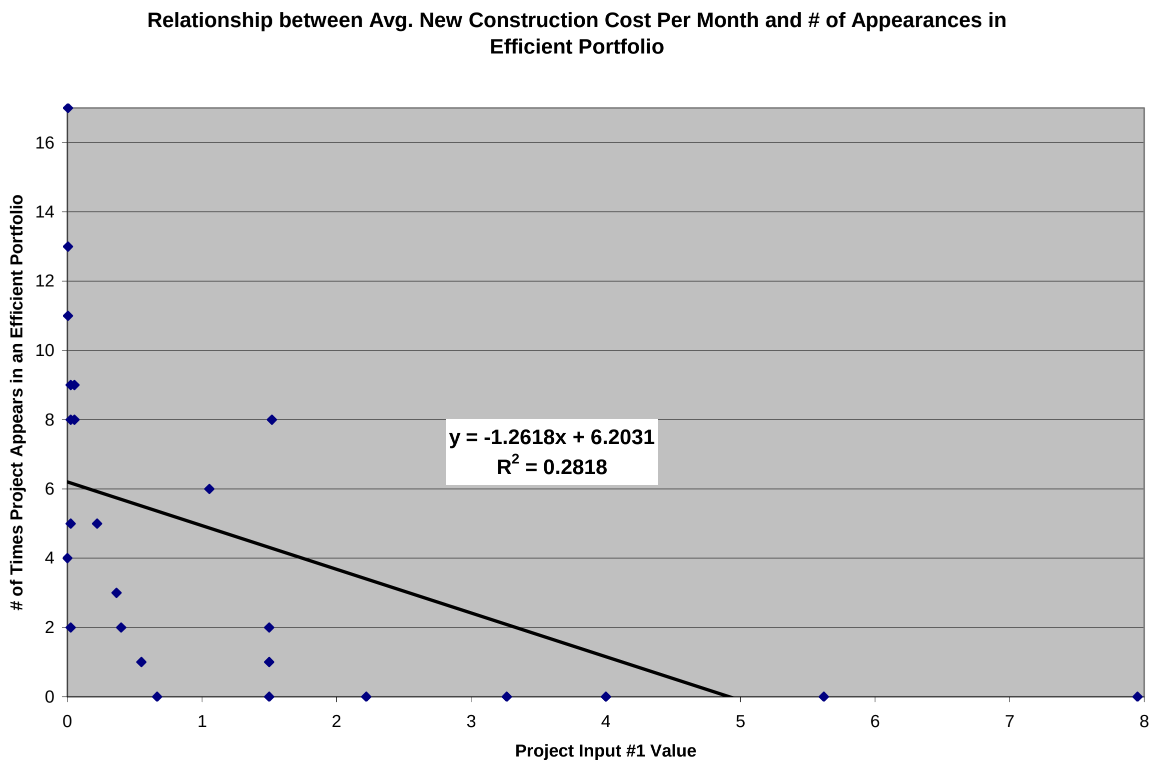


Figure 82. Regression Analysis to Determine Predictive Capability of Change in Input #1 Value versus Efficient Portfolio Composition.

The same type of analysis was performed on another single variable, Output #1, The Average Number of People Served, and as Figure 83 demonstrates, this relationship is even more tenuous, based solely on comparison of R^2 values.

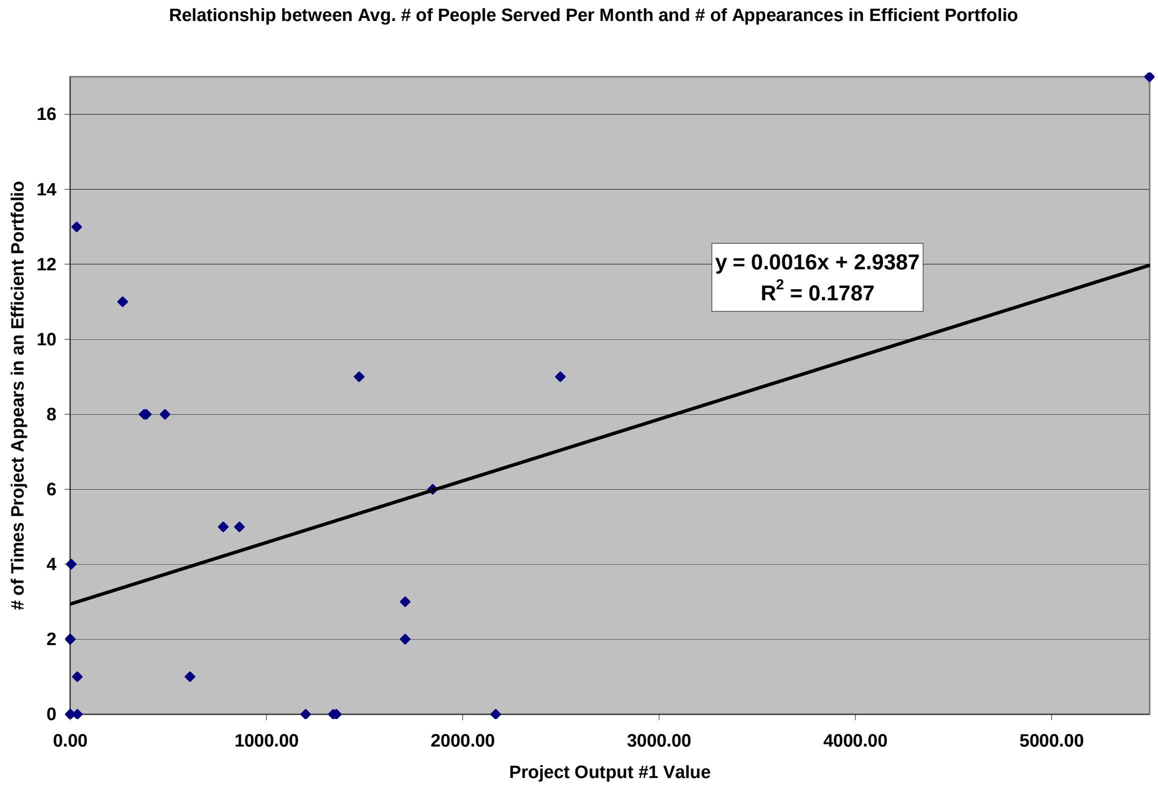


Figure 83. Regression Analysis to Determine Predictive Capability of Change in Output #1 Value versus Efficient Portfolio Composition.

Continuing this line of thought, this analysis includes a multiple-variable linear regression model in order to determine if combining the two variables together would offer any additional explanatory power. As Figures 84 and 85 appear to indicate based on their R^2 values, these multiple-regression models do seem to offer significantly greater explanatory power than the single linear regression models do. However, without getting into too much detail about "goodness of fit" indicators, it should be noted that, when comparing "adjusted R^2 values," that the two-variable model, Figure 84, with an adjusted R^2 value of 0.42311 is actually slightly greater than the adjusted R^2 value of the three-variable model, Figure 85, of 0.420. Both models were tested at the ninety five percent

level of confidence, and given the substantially smaller "p-values" for the input and output variables, this appears to support that claim.

SUMMARY OUTPUT FOR 2-VARIABLE MODEL

Regression Statistics	
Multiple R	0.686431287
R Square	**0.471187911**
Adjusted R Square	**0.423114085**
Standard Error	3.596624134
Observations	25

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	253.5744864	126.7872432	9.801339906	0.000904305
Residual	22	284.5855136	12.93570516		
Total	24	538.16			

	Coefficients	*Standard Error*	*t Stat*	***P-value***	*Lower 95%*	*Upper 95%*
Intercept	4.56488972	1.043235721	4.375703045	**0.00024098**	2.401351265	6.72842817
Input #1 Value	-1.2858053	0.368608263	-3.488270415	**0.002081849**	-2.050252046	-0.52135855
Output #1 Value	0.001691557	0.000602669	2.8067744	**0.010276205**	0.000441697	0.00294142

Figure 84. Regression of Change in Input #1 and Output #1 Values Versus Efficient Portfolio Composition.

SUMMARY OUTPUT FOR 3-VARIABLE MODEL

Regression Statistics	
Multiple R	0.702060177
R Square	**0.492888492**
Adjusted R Square	**0.420443991**
Standard Error	3.604937944
Observations	25

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	265.2528708	88.41762361	6.803670176	0.002220035
Residual	21	272.9071292	12.99557758		
Total	24	538.16			

	Coefficients	*Standard Error*	*t Stat*	***P-value***	*Lower 95%*	*Upper 95%*
Intercept	2.046288868	2.855203748	0.716687511	**0.481462387**	-3.891432355	7.984010091
Input #1 Value	-1.08826067	0.424177174	-2.565580461	**0.018021679**	-1.970385391	-0.206135949
Output #1 Value	0.001479139	0.000644284	2.29578637	**0.032084052**	0.000139277	0.002819002
Probability of Success	4.4663092	4.711456613	0.947967808	**0.353927937**	-5.331701166	14.26431957

Figure 85. Regression Analysis of Change in Input #1, Output #1, and Probability of Success Values Versus Efficient Portfolio Composition.

The data used to conduct the regression analysis is depicted in Figure 86. However, it should be noted that all of the data used to construct these regression models was simply obtained and consolidated from the numerous data sets shown previously.

Input #1 Value	Output #1 Value	Probability of Success	# of Times Appearing in Efficient Portfolio	Project #	Description
0.01	5499.45	81%	17	19	Electrical power distribution line segment A (rehab)
0.01	32.98	66%	13	20	Electrical power distribution line segment B (rehab)
0.01	267.05	66%	11	21	Electrical power distribution line segment C (rehab)
0.05	1472.59	81%	9	23	Road (surfaced) segment/ vehicle bridge B (rehab)
0.03	2497.04	66%	9	25	Communications tower (construct)
1.52	387.50	28%	8	18	Wastewater treatment plant (construct)
0.05	482.56	81%	8	22	Road (surfaced) segment/ vehicle bridge A (rehab)
0.03	376.27	81%	8	24	Road (surfaced) segment/ vehicle bridge C (rehab)
1.06	1846.79	53%	6	6	Rehabilitation of water distribution network
0.03	780.29	35%	5	16	Bank (estab. Modern transaction features)
0.22	862.50	66%	5	17	Rehab of Sewage and industrial waste collection/ transmission system
0.00	5.00	43%	4	5	Shrine (rehab)
0.37	1706.25	35%	3	7	Rehabilitation of WTP
0.03	0.00	66%	2	4	Railroad junction/ segment of rail (rehab)
0.40	0.00	66%	2	13	Oil pipeline section (rehab)
1.50	1706.89	66%	2	15	Road intersection/ interchange B (rehab)
0.55	36.50	28%	1	2	Airport: Utility building (electricity), co-generation, and rehab distribution system (construct)
1.50	610.58	66%	1	14	Road intersection/ interchange A (rehab)
1.50	36.50	66%	0	1	Airport: Runway (rehab)
0.67	1.50	35%	0	3	Hospital (rehab)
2.22	2167.75	66%	0	8	Construction of Transmission System
5.62	1356.25	35%	0	9	Construction of Water Treatment Plant
3.27	1340.54	53%	0	10	Construction of Distribution System/ Facilities
7.95	1200.00	35%	0	11	Construction of Reverse Osmosis (RO) Plant
4.00	0.00	23%	0	12	Oil storage facility (rehab)

Figure 86. Data Used to Conduct Regression Analysis (Figures 82 – 85).

With this information in mind, it is possible to construct a function that, as long as one assumes that the data values used within this thesis are within twenty five percent of the actual values on the ground, has the possibility of determining the number of times that an individual project is likely to appear in the most efficient portfolios based solely on input #1 and output #1 parameter values, with a reasonable degree of accuracy. The resulting two-variable, first order regression equation can be written in relatively non-mathematical terms as:

# of Times Appearing = 4.56 – 1.286 x Input #1 value + 0.00169 x Output #1 value

Simply stated, this regression equation provides the decision-maker with a reasonable predictive model as to the number of times an individual project will appear in an efficient portfolio. Even though the dependent variable is an absolute term, as opposed to a frequency or rate or appearance (i.e. the dependent variable is not the # of Times Appearing out of 100 possible instances), it is possible to perform this calculation to help serve as a screening criteria in order to gage whether a project should be considered for further analysis or not. However, before doing so, great care should be taken to ensure that the regression equation shown above is roughly equivalent to the regression provided by the data set in question, which is simple enough to do in practice, as long as the data is available. Finally, it should also be noted that a non-linear regression function, in some instances, might actually offer a better approximation than the linear function shown above. However, due to the desire to keep this thesis as concise as possible, this analysis was omitted.

Summary of Analysis

While it is necessary to be as accurate as possible whenever one conducts research, staff studies, and the like, the sensitivity analysis yielded that a single dominant parameter value, Output #1, Average Number of People Served, has the potential to generate the most variance in the results, with Input #1, New Construction Costs, also figuring prominently. Therefore, great care must be taken by staff analysts in scrutinizing the data which contributes to these particular parameter values, to include the process by which decision-maker specified weights are determined.

Furthermore, while design life was not explicitly evaluated within the sensitivity analysis, this parameter, after having consulted with a subject matter expert on hydrology and hydraulics, (conversation with Hains, April 2008) has the potential for great variance and must be analyzed closely - for an inaccurate design life parameter value has significant implications upon project costs and probability of success. Care must also be taken to construct reasonably accurate O&M cost versus reliability functions, since this also has life cycle implications. It should also be noted that while this study did not determine costs by using time value of money calculations, these calculations should certainly be considered when conducting this analysis within the theater of operations.

Additionally, one of the recurring themes throughout this analysis was that, absent cost (input) criteria, those projects that have many projects dependent upon them are typically those projects that reside in Lewis' "Level 1" infrastructure sectors, Water, Energy, and Telecom, and are most likely to be over-represented in "unconstrained cost" portfolios. However, one should also consider that the manner in which dependencies are aggregated will have significant implications on the types of projects that are included, or

not included in the case of railroad junctions, oil storage facilities, and oil pipeline sections. One cannot stress enough that the inclusion or exclusion of these types of projects could have potential short and long-term implications upon the affected population's economic system.

Furthermore, one also cannot overemphasize the necessity of understanding infrastructure project inputs, to include budget requirements and constraints, output measures of effectiveness and project probabilities of success, to include the method of aggregation considered, and project efficiency. It is also important to note that project interaction effects must also be considered, thereby resulting in a condition that causes portfolio characteristics to sometimes differ greatly from the characteristics of the individual projects found within the portfolios. An alternate formulation for the Critical Infrastructure Portfolio Selection Model would be to remove dependency calculations from the initial input and output parameter value entries, and implement this within the interaction matrices. However, based on the original formulation that was used within this thesis, it is possible to construct a function that has the possibility of determining the number of times that an individual project is likely to appear in the most efficient portfolios based solely on input #1 and output #1 parameter values, with a ninety five percent level of confidence. The contribution of such a tool within a stability operations environment, assuming that the data set presented in this thesis was sufficiently representative of the total population of infrastructure projects, is significant.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This thesis demonstrated a methodology, based largely on the approach developed by Eilat, et al., for the construction and analysis of efficient and balanced portfolios of critical infrastructure projects within a stability operations environment. Furthermore, this methodology, known as the Critical Infrastructure Portfolio Selection Model, is to help policy makers prioritize the allocation of limited resources. A secondary objective of this methodology was to facilitate simultaneous progress across the standard, stability operations' lines of effort: civil security, civil control, restore essential services, support to governance, and support to economic and infrastructure development (see Figure 87). Both objectives are vital and necessary when attempting to achieve national strategic goals within a stability operations environment.

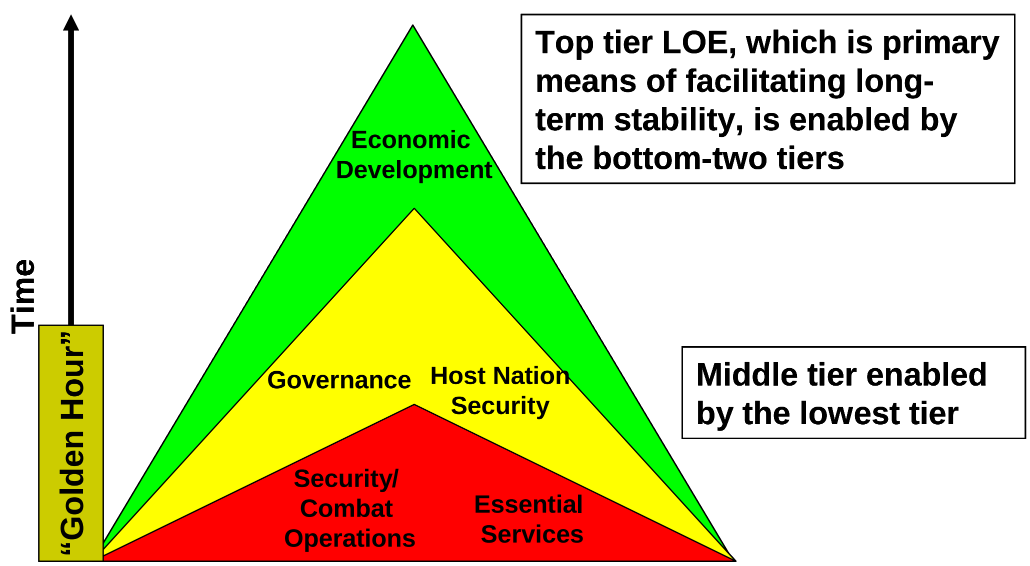


Figure 87. Line of Effort (LOE) "Hierarchy of Needs."

However, as many seasoned analysts know, the key to implementing an initiative successfully is to receive senior decision-maker “buy-in,” which usually comes when the analyst, or the analyst’s “champion,” is able to persuade decision-makers that the investment justifies the costs and the risks associated with system implementation.

The fact that the Critical Infrastructure Portfolio Selection Model is an operations research-based tool implies that it is both computationally and data intensive by nature. While the first claim is true, the Critical Infrastructure Portfolio Selection Model methodology can easily be converted into a robust decision-support system by a computationally-savvy individual; the second claim is untrue. Furthermore, many decision-makers are justifiably suspicious of any tool that attempts to “predict the future,” dictate a prescribed course of action based on the latest fad metric, or requires junior leaders to re-allocate scarce resources in an effort to simply manage additional data and intelligence collection efforts in order to support a tool that they neither use, nor understand. Therefore, the Critical Infrastructure Portfolio Selection Model attempts to do several things to allay these concerns. First, the sensitivity analysis section of Chapter 4 indicates that, based on the sample data set used in this thesis, portfolio composition, or the types of infrastructure projects that are selected for investment, is largely determined by a single, significant project input parameter, Input #1, the amount of capital budget/ new construction dollars required to undertake the project, and a single, significant project output parameter, Output #1, the weighted average of the number of people served by infrastructure project per month over the lifecycle of the infrastructure component. Since the budget parameter (Input #1) for a project is almost always the most readily available and widely documented piece of data for a particular infrastructure

project, this data requirement does not impose an additional data collection burden upon the commander on the ground. Similarly, since both the "population served" and "design life" parameter values, which are both required in order to calculate the value for Output #1, are readily obtained via routine infrastructure intelligence and reconnaissance efforts, this should also not present a particularly onerous data collection and management requirement. Of course, existing data and enterprise management systems such as USACE's GATER and IRMO's Iraq Reconstruction Management System (IRMS), along with SOPs at the soldier-level, would have to be modified slightly in order to implement the Critical Infrastructure Portfolio Selection Model to ensure that future collection efforts reflect these requirements. Specifically, the convention for capturing dependency relationships between infrastructure projects, both within the project database, as well as by soldiers on the ground, will most likely be the greatest source of consternation and confusion for those involved with it. Therefore, given the fact that the most significant parameter, Output #1, draws heavily upon the notion of these dependency relationships, great care must be taken to determine accurate infrastructure dependencies and the populations that are served as a result of these dependencies.

The second potential burden that appears to be overcome based on the results of the analysis is that the desired results of the Critical Infrastructure Portfolio Selection Model can be achieved more efficiently if an optimization (i.e. DEA) routine is not included as part of the final tool that gets implemented. An analysis of the plot of efficient and inefficient project portfolios based on the DEA results (Figure 74) indicates that there were numerous "efficient" portfolios of projects, based on a "simple" plot of data, which did not receive a DEA efficiency score of 1.0. Since the discrepancies

between “simple” and DEA measures of portfolio efficiencies were most likely due to the fact that “simple” efficiency calculations were based on rigid adherence to user-defined weights, and DEA efficiency calculations were determined by much less restrictive weight constraints, it appears that great time and effort could be saved when constructing a prototype of the Critical Infrastructure Portfolio Selection Model by omitting the DEA portion of the spreadsheet and database tool. An ancillary, and not inconsequential, benefit of omitting the DEA portion of the tool, is that by eliminating the need for the optimization package, the tool will be that much simpler, and more easily exportable, to a wider array of computer systems operating at the tactical level of war.

Two additional conclusions that should be drawn from this thesis include the significance of calculating probabilities of project success and the significance of aggregating project parameter data at the appropriate level. First, given that the magnitude of all of the output measures, to include the only output measured deemed to be significant, Output #1, are directly impacted by the probability of project success, the importance of calculating this value accurately cannot be overstated. Second, the fact that national-level infrastructure components were under-represented in the “efficient” portfolios stems from the manner in which project outputs, such as the number of people served, were aggregated. This was due to the fact that the “boundary conditions” for the projects considered within this analysis was limited to the specific area and specific projects under consideration. Electrical distribution power lines received high marks for levels of service (Output #1) and high probabilities of project success due in large part because the thesis does not consider the “upstream” part of the power grid, upon which the power lines were dependent for electricity. Conversely, rail lines and oil pipelines

while receiving “normal” probabilities of project success, received relatively small marks for levels of service (Output #1) since the analysis limited the scope of the “boundary conditions” to a single city within a single province of Iraq, where, in reality, a much larger portion of the Iraqi populace is probably dependent on the successful operation of these critical infrastructure projects. In any event, great care must be taken when determining the areas deemed necessary for aggregation, as well as when calculating the probability of project success to ensure that all other related project probabilities are accurate as possible.

Recommendations Based on Analysis

There is ample literature (e.g. National Security Strategy, U.S. Joint Force Command’s Joint Operating Environment (JOE): Trends and Challenges for the Future Joint Force Through 2030, U.S. Army Posture Statement) to suggest that the operating environment of the future will be replete with security conditions necessitating U.S. involvement in stability operations. Furthermore, Lawrence Yates, a retired professor of military history at the Command and General Staff College at Ft Leavenworth, Kansas clearly shows in his monograph, *The US Military’s Experience in Stability Operations, 1789 – 2005,* the important role that infrastructure construction, protection, and maintenance have played within stability operations over this period.

With this in mind, the following recommendations are made based on the analysis presented within this thesis. First, that the Critical Infrastructure Portfolio Selection Model, or another methodology similar in nature, be considered for further analysis and possible implementation within the USJFCOM, regional combatant command, and S/CRS communities. Even without full implementation, utilizing Lewis’ method of

critical node analysis to ascertain and aggregate infrastructure dependencies in order to determine the total number of people served by critical infrastructure projects, could be adopted relatively easily. Existing geospatial information systems available down to nearly the lowest levels of tactical command make this critical node analyses even more practical. However, one of the significant obstacles preventing this from happening is the lack of a common “infrastructure database” standard across all levels of command and leadership. The adoption of the DoD Real Property Classification System (RPCS), or other U.S.-based infrastructure classification standard, at the joint and interagency level, would greatly facilitate this process.

The next recommendation is that decision-makers at the aforementioned levels of command and leadership utilize the aggregation techniques mentioned previously, in order to more accurately determine the probabilities of project success. Once armed with this knowledge, risk mitigation efforts could be implemented more effectively – particularly if one were able to receive “buy-in” on these risk mitigation efforts from local, HN leaders.

The third recommendation is that this Critical Infrastructure Portfolio Selection Model, or another methodology similar in nature, be utilized by other governmental organizations, such as the World Bank, and Government Accountability Office (GAO). The intent is that this methodology could be used as an initial accountability tool to ensure that the primary departments engaged in international affairs, DoD and DoS, are serving as effective stewards of the American treasury system, while seeking to measure the progress towards national security objectives.

Recommendations for Future Research

The remainder of this thesis will make recommendations for further work based upon the conclusions arrived at on the basis of the analysis of the Critical Infrastructure Portfolio Selection Model. It is hoped that these recommendations for future research will also support of some of the most important considerations and initiatives reflected in David Kilcullen's 2007 presentation titled, "Counterinsurgency in Iraq: Theory and Practice." David Kilcullen, General David Petraeus' senior counterinsurgency (COIN) advisor in Iraq, suggests in the aforementioned presentation that COIN operations, which consist largely of stability operations, and pose the country's largest, near-term threat, must balance immediate and long-term perspectives and objectives (Kilcullen, 2007, Slide 60). It is for this reason that the Critical Infrastructure Portfolio Selection Model incorporated weighting mechanisms that enable decision-makers to prioritize various time horizons, zero to six months, six months to hour years, and four to ten years, within their portfolio selection strategies. Furthermore, while this thesis placed heavy, sixty percent, emphasis on a project's ability to deliver services to an affected population between zero to six months of initiation, developers would be well served in conducting a separate sensitivity analysis on these particular output weights with a new data set before implementing the Critical Infrastructure Portfolio Selection Model as part of a more comprehensive DSS. Similarly, more thorough robustness checks should be performed on the regression equation terms shown at the conclusion of Chapter 4 in order to verify the significance of the Input #1 and Output #1 parameter values.

Kilcullen also recommends that coalition metrics and measures of effectiveness be scrutinized intensely, and always through an appropriate lens of interpretation and

judgment (Kilcullen, 2007, Slide 65). Fortunately, there is ample justification for the selection of the output measures of effectiveness used within the Critical Infrastructure Portfolio Selection Model. However, a measure of effectiveness that was not used, but should certainly be considered when assessing the long-term effectiveness of a national strategy, as Kilcullen implies, is the amount of foreign-direct investment (FDI) that foreign companies are pouring into the affected country - particularly in non-primary commodity economic sectors. Both Collier and Hoeffler, as well as Thomas Oatley, in his third edition of *International Political Economy: Interests and Institutions in the Global Economy* state that FDI, particularly in non-primary commodity export sectors, is a sound measure of effectiveness. With this in mind, an input-output, or systems dynamic, model which includes the host nation's economic sectors and other significant entities such as the level of infrastructure sector development and the level of security, is probably the next logical research contribution before complete system implementation would make sense. The input-output model helps identify economic sectors that provide the greatest "value added," while the purpose of the systems dynamic model is to reflect relationships and determine rates of change amongst model components as parameter values are changed elsewhere in the model. On a similar note, Kilcullen postulates that small, local programs, not dependent upon commander's emergency response program (CERP) funds, tend to perform better, since local "buy-in" and long-term viability is more likely, in the long run, and this recommendation is supported by the analysis results of the Critical Infrastructure Portfolio Selection Model (Kilcullen, 2007, Slide 60).

Finally, Kilcullen states that one of the pressing needs of every organization that work in Iraq, and ostensibly, in any COIN or stability operations environment, is to

“triage the environment,” and stick to priorities (Kilcullen, 2007, Slide 65). While it may be impossible to ever confirm whether any of the proposed recommendations will succeed in yielding a single tool that enables this worthwhile goal, the Critical Infrastructure Portfolio Selection Model is certainly a step towards achieving this desired vision, in an effort to bring members of the quantitative and qualitative analytical communities together, in support of both senior decision-makers and commanders engaged at the lowest levels of command in this challenging contemporary operating environment.

APPENDIX A

OVERVIEW OF A POSSIBLE DATA MANAGEMENT LAYER

As mentioned in the final section of Paragraph 3 and alluded to throughout the thesis, the key to implementing the Critical Infrastructure Portfolio Selection Model as part of a larger, information management, or decision support, system, is to manage the data effectively. Towards that end, this appendix hopes to briefly address this data management issue. Furthermore, while not a significant part of this thesis, the author spent a considerable amount of time considering this issue, and as mentioned throughout this research, is generally familiar with some of the existing information management systems which a fully implemented Critical Infrastructure Portfolio Selection Model could be integrated with.

As mentioned in Chapter 3, the steps associated with developing an effective database (as indicated in the MS Access 2003 Bible) include:

Step 1: Overall System Design

Step 2: Report (Output) Design

Step 3: Data (Fields) Design

Step 4: Table (Relationships) Design

Step 5: Field (Validation) Design

Step 6: Form (Input) Design

Step 7: Menu (Automation) Design

With respect to the overall system design, step 1, the data layer of the Critical Infrastructure Portfolio Selection Model should be able to:

a. Permit data entry for infrastructure projects
b. Maintain input (budget) requirements for projects
c. Maintain expected output contributions for projects
d. Maintain threat info/ failure modes for projects
e. Maintain dependency info for projects – this dependency info must relate a given project to outputs from other projects
f. Maintain probability of failure modes for projects

Each of these database requirements are captured in the author's master spreadsheet shown in Figure 88 (below).

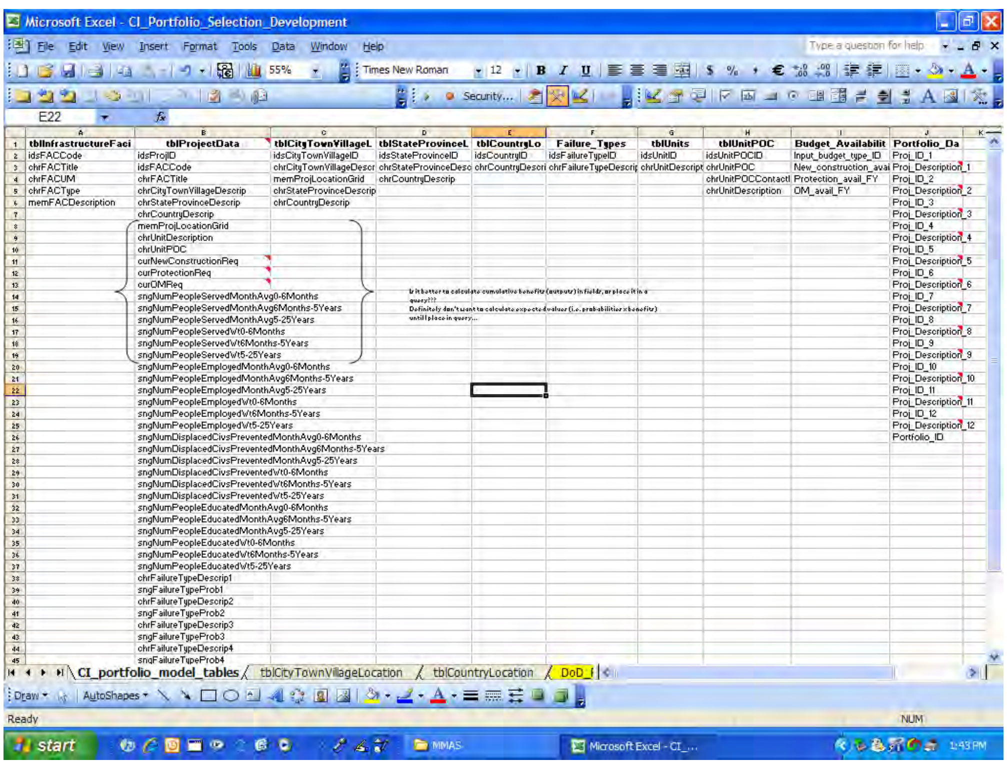


Figure 88. Spreadsheet Identifying Potential Data Tables and their Contents.

A trial set of database tables, reflecting the requirements shown in Figure 88, were developed using MS Access and are shown in Figure 89 (below).

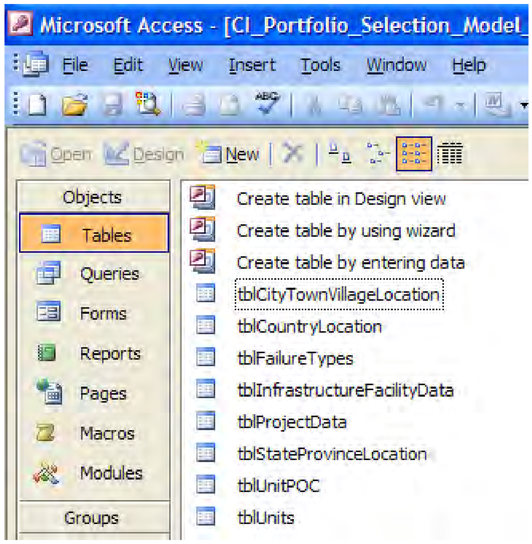


Figure 89. Possible Data Tables Contained Within a Proposed Database.

Specific field contents are shown using an extract from the DoD Real Property Classification System (RPCS, 2005) (Figure 90).

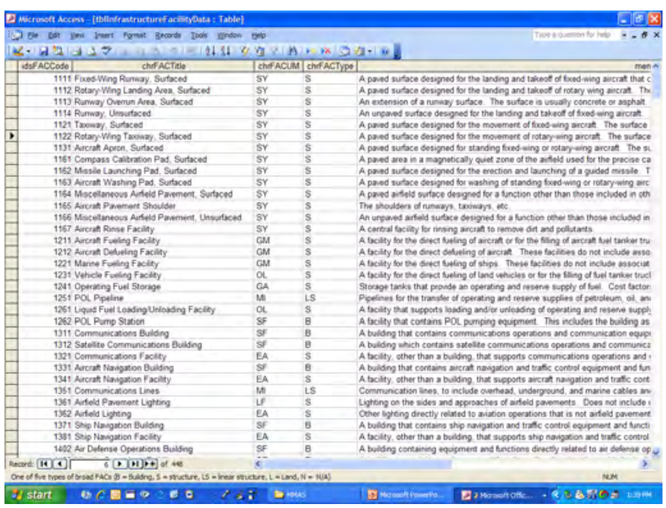


Figure 90. Contents of the Infrastructure Facility Data Table, Based on the DoD's Real Property Classification System (RPCS).

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